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Image Intensifier System Resolution Based on Laboratory Measured Parameters

by

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Suitability of any analytical model is entirely dependent on how well the model prediction fits the actual measured data under real conditions. The primary intent of formulating this laboratory version of an image intensifier performance model considered the following premise. If an image intensifier model cannot accurately predict laboratory measured performance (where all test conditions and parameters are controlled and known), then it cannot be viable for predicting field performance (where conditions cannot be controlled nor are well known). The report details the basis of the model and its complete derivation. The Appendix presents numerous examples that compare the model's output with actual performance data measured by observers. The reader is referred to a planned update of the NVESD Image Intensifier Performance Model to be released in early calender year 1994. The revised performance model will include this work on limiting resolution and establish the link between limiting resolution and the traditional Minimum Resolvable Contrast utilized for the prediction of observer performance in field conditions.

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Preface

Having been educated as an electronics engineer, the confusions surrounding the physical characterization of optics and electro-optics has been quite a challenge to put into perspective. Whereas electronic circuit modeling is a well-matured discipline, electro-optics modeling is still stumbling through theory and equations to determine what the human eye "sees" with devices that aid the visual sense. Suitability of any analytical model, whether it be an electronic circuit or an optical system, is primarily dependent on how well the model prediction fits the actual measured data under real conditions. Unfortunately, the converse to this premise is usually ignored: How well is the measured data interpreted by and incorporated into the analytical model? Those of you who probe into this dissertation should recognize this latter concern, for it is common to have experienced, as you may have, many solutions to problems where two wrongs yield a correct solution.

The origin of this model began about 13 years ago when a paper by E. A. Richards, dated 1967, caught my attention: "Fundamental Limitations in the Low Light-Level Performance of Direct-View Image-Intensifier Systems." At that time, having been intimately involved in image intensification for a decade, and recognizing a need for correlating intensifier parameters with lab-measured system performance, the temptation to try Richards' formulation was compelling. Over the years the various parameters that dictate the intensifier system performance were added to this foundation. The sequence of this report follows the slow and sporadic evolution of the model over that period. Most recently the aspect of one/two eye systems (monocular, binocular, and biocular) was formulated, which presents a theoretical approach for expressing the way the brain interprets the image(s) from one or both eyes. It should not be surprising for you who are electronic engineers to recognize a circuit analogy in this formulation: with two imaging devices cascaded, two quantities add (as resistors in series); and with two imaging devices in parallel, there is a product over sum of two quantities (as resistors in parallel). It would be most appealing to eventually describe this electro-optic system with an equivalent electrical circuit counterpart.

Care has been taken to note all assumptions, speculations, and precautions while developing the model. Of course the initial attempt to adapt Richards' equation was viewed in a speculative manner until it was found to correlate well with observer data. Comments that either substantiate or disprove these assumptions or speculations are welcome.

Basis for the Model

The spatial resolution at the input photosurface, limited by the statistical photon noise of the radiation collected from the target by the objective and by the integration time of the system, is derived by Richards[1] according to the following:

$$R_p = \frac{C_b}{4kA_o}\sqrt{\frac{StL_o}{(2-C_b)\,q}} \quad \textit{line pairs/unit length} \tag{1}$$

where:

C_b = contrast of target, $(L_o - L_s)/L_o$
L_o = higher target luminance
L_s = lower target luminance
k = threshold signal-to-noise factor for the visual discrimination between adjacent areas of the target in the presence of photon noise, as derived by Rose.[2]
A_o = relative aperture of the objective (focal length/diameter)
S = integral sensitivity of input photosurface (e.g. microamps per lumen)
t = integration time, assumed to be that of the eye (viz. 1/5th of a second)
q = charge on the electron

A unit analysis of Equation 1 will show that the "unit length" is "foot" with luminance values in foot lambert. Conversion to the more familiar term of lp/mm requires a constant multiplier of 3.28×10^{-3} [ft/mm]. Other conversions necessary to reformulate the equation with standard measurement parameters of intensifier systems include the following:

(a) It will be the convention throughout this formulation to define contrast in the same terms as modulation transfer function:

$$C = \frac{High - Low}{High + Low} \tag{2}$$

Therefore, C_b in Equation 1 may be replaced by C with the following substitution:

$$C_b = \frac{2C}{1 + C} \tag{3}$$

(b) A_o as defined by Richards is actually the F-number of the input optic. Since he assumed the optic to be ideal (i.e., transmittance = 1.0), this value may be more accurately replaced with the T-number of the input optic as follows:

$$A_o = \frac{F_{no}}{\sqrt{t_r}} = T_{no} \tag{4}$$

(c) Since the cathode sensitivity of a packaged intensifier tube cannot be measured, this parameter may be expressed as a function of the signal-to-noise input that occurs at the photosurface. It must be realized that the bandwidth of the S/N measure is 10 hz noise equivalent

on a spot diameter of 0.2mm at a light level of 1 x 10^{-5} fC of 2856K blackbody spectral distribution. Since the input is shot noise, the relationship is:

$$S/N_{in} = \sqrt{\frac{\bar{I}}{2q\Delta f}} \tag{5}$$

where:

I = average cathode current
q = elementary charge = 1.602 x 10^{-19} coulomb
Δf = noise equivalent bandwidth = 10 hz

From the relationship given in Equation 5 it can be shown that the cathode sensitivity, S, is related to the input S/N as follows:

$$S = 0.943 \times (S/N_{in})^2 \times 10^{-6} \quad amps/lumen \tag{6}$$

Substituting the formulas in Equations 3, 4, and 6 into Equation 1 yields the following:

$$R_p \ [lp/mm] = 2813 \times \frac{C}{\sqrt{1+C}} \times \frac{S/N_{in}}{T_{no}} \times \frac{\sqrt{t}}{k} \times \sqrt{L_o} \tag{7}$$

The quantity R_p, as defined by Richards, is the limiting spatial resolution that occurs at the input photosurface. It does not account for the subsequent degradations caused by the tube's noise figure and MTF, and the eye's limitations. However, Equation 7 may be expanded to represent the resolution attained at the output of the image tube as follows:

(a) Replace S/N_{in} with S/N_{out} x CF. The output signal-to-noise as measured and specified accounts for the noise figure of the MCP (but not for the integrating effect of the phosphor screen).

(b) Replace C with C_{out} which represents the resultant output contrast reduced by the effect of the image tube MTF; replace L_o with H to represent the higher luminance of the target or background; and replace R_p with R_c to represent this condition.

Then,

$$R_c = 2813 \times \frac{C_{out}}{\sqrt{1+C_{out}}} \times \frac{\sqrt{H}}{T_{no}} \times \frac{\sqrt{t}}{k} \times (S/N_{out} \times CF) \tag{8}$$

A correction factor, CF, is applied to the S/N_{out} term for the following reasons:

1. The signal-to-noise ensemble is measured over 0.1 sec., whereas the eye integration time is considered to be 0.2 sec.

2. The actual measurement light level for the signal-to-noise output is 1.3 x 10^{-5} fC at the focal plane of the input optic. Note that the signal-to-noise input was characterized at 1 x 10^{-5}fC.

3. It will be assumed that the resolving area of interest is a square pixel for the target and for the background dictated by the minimum line width imaged at the cathode. Therefore, since the signal-to-noise is measured with a 0.2mm diameter spot, the equivalent square pixel (0.2mm x 0.2mm) would have its signal-to-noise increased by $(4/\pi)^{1/2}$.

4. Since the signal-to-noise measure removes the integrating effect of the phosphor screen, its effect must be introduced in order to represent the actual S/N seen by the eye. This quantity is a function of the phosphor type only and has been termed the K-factor (K_f).

Applying these effects together, the correction factor for the measured signal-to-noise is:

$$CF = \sqrt{\frac{0.2\ \text{sec}}{0.1\ \text{sec}}} \times \sqrt{\frac{1\times10^{-5}}{1.3\times10^{-5}}} \times \sqrt{\frac{4}{\pi}} \times K_f \tag{9}$$

Therefore, $CF = 1.4 \times K_f$ where K_f = 1.24 for RCA 1052 phosphor,
1.19 for P-20 phosphor, and
1.3 for P1/P39 phosphor

Assuming that the threshold signal-to-noise (k) equals 2.0 for 50% probability of detection, that the integrating time for the eye (t) is 0.2 sec, and substituting Equation 9 into Equation 8 yields the following:

$$R_c = 881 \times \frac{C_{out}}{\sqrt{1+C_{out}}} \times \frac{\sqrt{H}}{T_{no}} \times S/N_{out} \times K_f \tag{10}$$

The solution for output resolution as presented in Equation 10 would be difficult to compute since the output contrast is a function of the resolution itself. However, the equation may be rearranged with a solution for the high light level input, H, as follows:

$$H = \left(\frac{R_c T_{no}}{881\ S/N_{out}\ K_f}\right)^2 \times \frac{1 + C_{out}}{C_{out}^2} \tag{11}$$

Equation 11 provides an approximate solution for the resolution provided by unity magnification systems since EBI is assumed to be zero and the implication of gain and the effects of the eye have not yet been introduced.

Thus far the signal-to-noise term in the equations has been defined as being measured over a 0.2mm spot diameter. It has been determined that it would be more appropriate to define the signal-to-noise over a constant angular input rather than a linear spot size on the photocathode. Since the measure of S/N_{out} is done with an objective having an EFL of 26.8mm, the angular input is 0.2/26.8 radians. Therefore, system input optics having their effective focal length equal to EFL_i would result in a spot diameter equal to 0.2 x EFL_i/26.8mm. Since signal-to-noise varies directly with the spot diameter, the system signal-to-noise (S/N_s) would equal the measured signal-to-noise times EFL_i/26.8:

$$S/N_s = S/N_{out} \times \frac{EFL_i}{26.8} \tag{12}$$

Replacing S/N_{out} in Equation 11 with S/N_s in Equation 12 yields:

$$H = \left(\frac{26.8 \times R_c T_{no}}{881 \times EFL_i \times S/N_{out} \times K_f}\right)^2 \times \frac{1 + C_{out}}{C_{out}^2} \tag{13}$$

EBI Contribution

The effect of EBI will now be introduced. Since EBI is defined as the equivalent background (Lumen/cm^2) at the input to the photocathode (at 21 degrees centigrade), the equivalent brightness (fL) at the target (e) would be as follows:

$$e = 929\left[\frac{cm^2}{ft^2}\right] \times 4T_{no}^2 \times EBI \times 2^{(T-21)/T_c} \tag{14}$$

where T = ambient temperature (°C)
T_c = temperature coefficient = 3°C for 2nd Gen
= 4°C for 3rd Gen

EBI effectively reduces the target contrast. Recall from Equation 2 the definition of target contrast. The image tube's EBI will incur a reduction of that contrast as follows:

$$C_e = \frac{H - L}{H + L + 2e} \tag{15}$$

or equivalently:

$$C_e = \frac{HC}{H + e(1 + C)} \tag{16}$$

The C_{out} term in Equation 13 is equal to the effective target contrast at the photocathode (C_e) times the contrast transfer of the image tube (C_m). Substituting this for C_{out} and letting K^2 equal the first term of Equation 13 results in:

$$H = K^2 \times \frac{1 + C_e C_m}{(C_e C_m)^2} \tag{17}$$

where H = the higher luminance level of either target or background.

Substituting Equation 16 into Equation 17, and reducing the equation yields the following:

$$H^3 = H^2 \frac{K^2(1 + CC_m)}{(CC_m)^2} + H\frac{K^2 e(1 + C)(2 + CC_m)}{(CC_m)^2} + \frac{K^2 e^2 (1 + C)^2}{(CC_m)^2} \tag{18}$$

where $K = 26.8 \times R_c \times T_{no}/(881 \times EFL_i \times S/N_{out} \times K_f)$

The solution of the cubic Equation 18 for H gives the high light luminance level required to resolve a target having R_c lp/mm at the photocathode image plane. The system's angular resolution at the input (R_i [cy/mr]) is:

$$R_i = \frac{R_c \times EFL_i}{1000} \tag{19}$$

The angular resolution presented to the eye (R_s [cy/mr]) is:

$$R_s = \frac{R_c \times EFL_i}{1000 \times M} \tag{20}$$

where M is the system magnification.

The light level as seen by the eye is approximately the gain of the system (G_s [fL/fL]) times H.

MTF Contribution

Attention will now be turned to the contribution of MTF implied by the C_m term in Equations 17 and 18. C_m is a function of the modulation transfer function (MTF) of the intensifier tube and the spatial shape of the target, assumed to be on a uniform background. Spatial shapes of primary interest are periodic square waves, tri-bar targets, and singular bar targets.

Periodic Square Wave Analysis

The simplest spatial shape to analyze is the periodic square wave (amplitude = 1) since it is analytically described by its Fourier components in the double-sided frequency domain:

$$F(nf) = \frac{1}{2}\frac{\sin(n\pi/2)}{n\pi/2} \tag{21}$$

where F(0) = 1/2, and n = n^{th} component at $\pm nf$.

Given a periodic input spatial frequency of f lp/mm at 100% contrast at the input of an image tube whose MTF is defined as MTF(f), the resultant output high level, $H_p(f)$, and the output low level $L_p(f)$ will be:

$$H_p(f) = \frac{1}{2} + 2\sum_{n=1}^{\infty} MTF(nf)\ \frac{1}{2}\frac{\sin(n\pi/2)}{n\pi/2} \tag{22}$$

$$L_p(f) = \frac{1}{2} - 2\sum_{n=1}^{\infty} MTF(nf)\ \frac{1}{2}\frac{\sin(n\pi/2)}{n\pi/2} \tag{23}$$

The resultant output image contrast, designated as the contrast transfer function CTF(f), will be:

$$CTF(f) = \frac{H_p(f) - L_p(f)}{H_p(f) + L_p(f)} = 2\sum_{n=1}^{\infty} MTF(nf)\ \frac{\sin(n\pi/2)}{n\pi/2} \qquad (24)$$

where CTF(0) = 1, and n = n^{th} component at nf.

In analytical form Equation 24 can be expressed as follows:

$$CTF(f) = \frac{4}{\pi}\left[MTF(f) - \frac{MTF(3f)}{3} + \frac{MTF(5f)}{5} - \frac{MTF(7f)}{7} + \cdots\right] \qquad (25)$$

The output image contrast can now be expressed for the periodic square wave spatial input condition whereby the C_m term in Equation 18 is simply equal to CTF(R_c), where f=R_c in Equation 25.

Singular Positive Bc Target Analysis

Singular bar targets are described in the frequency domain by the Fourier integral. Let τ = the positive pulse width (mm) with unity amplitude, and f = the spatial frequency components (cy/mm). Then the Fourier transform of the single pulse is:

$$F(f) = \tau\frac{\sin(\pi f\tau)}{\pi f\tau} \qquad (26)$$

Given a single pulse of width τ mm, amplitude = +1 at 100% contrast at the input of an image tube whose MTF is defined as MTF(f), the resultant output high level, $H_s(\tau)$, will be:

$$H_s(\tau) = \int_0^{\infty} MTF(f)\,2\tau\frac{\sin(\pi f\tau)}{\pi f\tau}\,df \qquad (27)$$

The output low level, L_s, will be zero. Although the contrast transfer under this condition is unity, the only effect is a reduction of the peak amplitude. Therefore, for the condition of a non-zero low level background, the output contrast can be determined as follows:

Let the input contrast, C, be defined as (H - L)/(H + L) as in Equation 2. Assuming a tube gain of unity, the output low level will be unchanged: ie, L_{out} = L. However the peak-to-peak amplitude of the pulse will be reduced by $H_s(\tau)$:

$$H_{out} - L_{out} = (H - L) \times H_s(\tau) \qquad (28)$$

or, solving for H_{out}:

$$H_{out} = L + H_s(\tau) \times (H - L) \qquad (29)$$

Since the output contrast C_{out} is defined as $(H_{out}-L_{out})/(H_{out}+L_{out})$, it can be shown that:

$$C_{out} = \frac{C\,H_s(\tau)}{1 - C[1 - H_s(\tau)]} \tag{30}$$

Therefore, for a singular high level pulse, the C_m term in Equation 18 is:

$$C_m = \frac{H_s(\tau)}{1 - C[1 - H_s(\tau)]} \tag{31}$$

where $H_s(\tau)$ is defined by Equation 27, and $R_c = 1/(2\tau)$.

Singular Negative Bar Target Analysis

The analysis for a low level pulse condition is similar:

Let the input contrast, C, be defined as (H - L)/(H + L) as in Equation 2. Assuming a tube gain of unity, the output high level will be unchanged: ie, $H_{out} = H$. However the peak-to-peak amplitude of the pulse will be reduced by $H_s(\tau)$:

$$H_{out} - L_{out} = (H - L) \times H_s(\tau) \tag{32}$$

or, solving for L_{out}:

$$L_{out} = H - H_s(\tau)\,(H - L) \tag{33}$$

Since the output contrast Cout is defined as $(H_{out}-L_{out})/(H_{out}+L_{out})$, it can then be shown that:

$$C_{out} = \frac{C\,H_s(\tau)}{1 + C[1 - H_s(\tau)]} \tag{34}$$

Therefore, for a singular low level pulse, the C_m term in Equation 18 is:

$$C_m = \frac{H_s(\tau)}{1 + C[1 - H_s(\tau)]} \tag{35}$$

where $H_s(\tau)$ is defined by Equation 27, and $R_c = 1/(2\tau)$.

Tri-Bar Target Analysis (white on black)

Tri-bar targets present an awkward situation due to the effect of windowing a periodic square wave pattern. The analysis would be to convolve the Fourier transform of the window function with the Fourier components of a square wave (equivalent to multiplying the window function with a periodic square wave) to obtain the fourier transform of the input function. Multiplying this by the MTF of the image tube will give the Fourier transform of the output image. The analysis will show that there exist three unique contrast values due to the spatial geometry. The lowest contrast occurs at the first white bar and adjacent dark bar. The contrast of this pair, $H_{3p}(f)$, can be shown to exhibit an approximate solution according to the following formula:

$$H_{3p}(f) = \frac{[CTF(f)]^4}{[CTF(f)]^3 + 3.1443\times10^{-4}} \quad (36)$$

The error introduced by this approximation is shown in the following tables for a 25 lp/mm and 41 lp/mm image tube respectively:

Freq[f]	MTF(f)	CTF(f)	H_{3p}(f) exact	H_{3p}(f) Eqn 36	Error
0	1	1	1	1	0%
5	.6752	.7849	.7938	.7844	-1%
10	.3843	.4810	.4904	.4796	-2%
15	.2000	.2539	.2514	.2491	-1%
20	.09744	.1239	.1036	.1063	+3%
25	.04500	.0572	.0191	.02134	+12%

Freq[f]	MTF(f)	CTF(f)	H_{3p}(f) exact	H_{3p}(f) Eqn 36	Error
0	1	1	1	1	0%
5	.8028	.8817	.8882	.8813	-1%
10	.5931	.7059	.7176	.7053	-1%
15	.4201	.5211	.5328	.5199	-2%
20	.2886	.3640	.3706	.3616	-2%
25	.1935	.2454	.2432	.2403	-1%
30	.1271	.1619	.1491	.1507	+1%
35	.08200	.1043	.08037	.08167	+2%
40	.05206	.0664	.03180	.03201	+1%

For an input contrast of C, the resultant output image contrast will be C x $H_{3p}(f)$. Therefore, for a tri-bar target (white on black), the C_m term in Equation 18 is:

$$C_m = H_{3p}(f) \quad (37)$$

where $H_{3p}(f)$ is defined by Equation 36.

Tri-Bar Target Analysis (black on white)

The analysis will show that there exist three unique contrast values due to the spatial geometry. The lowest contrast occurs at the first black bar and adjacent white bar. The contrast of this pair, $H_{3n}(f)$, can be shown to exhibit an approximate solution according to the following formula:

$$H_{3n}(f) = .043 \times [CTF(f)]^2 + CTF(f) - .0426 \qquad (38)$$

The error introduced by this approximation is shown in the following tables for a 25 lp/mm and 41 lp/mm image tube respectively:

Freq[f]	MTF(f)	CTF(f)	$H_{3n}(f)$ exact	$H_{3n}(f)$ Eqn 38	Error
0	1	1	1	1	0%
5	.6752	.7849	.7699	.7688	0%
10	.3843	.4810	.4509	.4483	-1%
15	.2000	.2539	.2170	.2141	-1%
20	.09744	.1239	.08395	.08196	-2%
25	.04500	.0572	.01551	.01474	-5%

Freq[f]	MTF(f)	CTF(f)	$H_{3n}(f)$ exact	$H_{3n}(f)$ Eqn 38	Error
0	1	1	1	1	0%
5	.8028	.8817	.8700	.8725	0%
10	.5931	.7059	.6815	.6847	0%
15	.4201	.5211	.4881	.4902	0%
20	.2886	.3640	.3260	.3271	0%
25	.1935	.2454	.2048	.2054	0%
30	.1271	.1619	.1199	.1204	0%
35	.08200	.1043	.06163	.06217	+1%
40	.05206	.0664	.02323	.02399	+3%

For an input contrast of C, the resultant output image contrast will be C x $H_{3n}(f)$. Therefore, for a tri-bar target (black on white), the C_m term in Equation 18 is:

$$C_m = H_{3n}(f) \qquad (39)$$

where $H_{3n}(f)$ is defined by Equation 38.

Output Target Brightness

It is intuitively assumed that the output image brightness from an intensifier tube is the input brightness times the gain of the intensifier tube. However, the actual output brightness is decreased by the effect of the image tube's MTF which incurs a reduction of the peak amplitude of the input by spreading the incident irradiance across the output. For example, refer to Equation 22 which relates the high level output for a periodic square wave input. For low frequencies where the MTF is near unity, the output high level is also unity (assuming an image tube gain of unity). However, for higher spatial frequencies where the MTF approaches zero, the output peak amplitude approaches 1/2.

Computing the output brightness of an image tube is necessary to quantify the brightness level perceived by the eye in completing this model. The effect of the eye resolution limit versus brightness is discussed later.

The following discussion centers on the gain reduction factor (G_r) incurred by the image tube spreading the input flux of the image across the output. This quantity is uniquely established for each of the five spatial shapes discussed previously. The high light output (where EBI = 0) will be described according to the following:

$$H_{out} = G \times H_i(R_c) \times G_r(R_c) \tag{40}$$

where:

H_{out} = the high light output at Rc lp/mm, (fL)
G = the gain of the image intensifier tube, (fL/fC)
$H_i(R_c)$ = he high light input at Rc lp/mm, (fC)
$G_r(R_c)$ = the gain reduction factor

Periodic Square Wave Gain Reduction

Given that for a unity gain condition, the average (DC component) input light level equals the average output light level, it can be shown that:

$$H_{out} = H + L - L_{out} \tag{41}$$

where H and L refer to the high and low input respectively. The low input and low output can be expressed in terms of high input and high output as follows:

$$L = H\left(\frac{1 - C}{1 + C}\right) \tag{42}$$

and

$$L_{out} = H_{out}\left[\frac{1 - C \times CTF(R_c)}{1 + C \times CTF(R_c)}\right] \tag{43}$$

Substituting Equations 42 and 43 into 41, and solving for H_{out} yields the following:

$$H_{out} = H \times \frac{1 + C \times CTF(R_c)}{1 + C} \tag{44}$$

Therefore,

$$G_r(R_c) = \frac{1 + C \times CTF(R_c)}{1 + C} \tag{45}$$

Singular Positive Bar Target Gain Reduction

The gain reduction for this input condition can be derived from Equation 29 by substituting the following quantity for L:

$$L = H\left(\frac{1 - C}{1 + C}\right) \tag{46}$$

Solving Equation 29 with this substitution for H_{out} yields:

$$H_{out} = H \times \frac{1 - C + 2C\,H_s(\tau)}{1 + C} \tag{47}$$

Therefore,

$$G_r(R_c) = \frac{1 - C + 2C\,H_s(\tau)}{1 + C} \tag{48}$$

Singular Negative Bar Target Gain Reduction

Since the peak amplitude for this input condition is spatially constant, there is no reduction in the gain. Therefore, the gain reduction factor, $G_r(R_c)$ is simply unity.

Tri-Bar Target (white on Black) Gain Reduction

Because of the complexity in determining the high level of the lower contrast pair of lines in this geometry, an approximation for the gain reduction will be used. For the condition of 100% contrast input, the approximation for the gain reduction is:

$$G_{r1} = \frac{1}{2.45} + \frac{CTF(R_c)}{1.69} \tag{49}$$

For an input contrast condition less than 100% where the low light input is greater than zero,

$$H_{out} = L + (H - L) \times G_{r1} \tag{50}$$

where:

$$L = H \frac{1 - C}{1 + C} \tag{51}$$

Substituting Equations 49 and 51 into 50 and reducing yields:

$$H_{out} = H \times \frac{1 + C\,[1.1834\,CTF(R_c) - .1837]}{1 + C} \tag{52}$$

Therefore,

$$G_r(R_c) = \frac{1 + C\,[1.1834\,CTF(R_c) - .1837]}{1 + C} \tag{53}$$

Tri-Bar Target (black on white) Gain Reduction

Because of the complexity in determining the high level of the lower contrast pair of lines in this geometry, an approximation for the gain reduction will be used. For the condition of 100% contrast input, the approximation for the gain reduction is:

$$G_{r2} = \frac{1}{1.8} + \frac{CTF(R_c)}{2.25} \tag{54}$$

For an input contrast condition less than 100% where the low light input is greater than zero,

$$H_{out} = L + (H - L) \times G_{r2} \tag{55}$$

where:

$$L = H \frac{1 - C}{1 + C} \tag{56}$$

Substituting Equations 54 and 56 into 55 and reducing yields:

$$H_{out} = H \times \frac{1 + C\,[.88889\,CTF(R_c) + .11111]}{1 + C} \tag{57}$$

Therefore,

$$G_r(R_c) = \frac{1 + C\,[.88889\,CTF(R_c) + .11111]}{1 + C} \tag{58}$$

This reduction in apparent gain occurs only with the two high peaks between the black bars. This effect is discussed here for analytical purposes and to inform the reader that it was not neglected in developing the model. However, it is assumed that the gain reduction of this pair of lines is not the predominant factor in establishing the brightness to the eye; rather it is assumed that the brightness to the eye is determined by the background brightness of this target type, and not the brightness of the bars. Therefore, for this condition $G_r(R_c)$ is unity since there is no effect of gain reduction on the background level of brightness.

Total System Performance

The modeling equations thus far provide a means to characterize the performance of the intensifier system alone. They do not account for the limitations imposed by coupling a detector, such as the human eye (direct view) or a CCD camera (remote view), to the intensified output. The model thus far, however, may serve as an indicator of relative performance which will predict the limiting performance that can be attained by the intensifier system itself. The discussion which follows will consider the direct view mode of the intensifier system in which the effects of human eye perception will be integrated for completing the performance model of the complete image intensifier system.

Human Eye Performance Limitation

The performance characteristics of the human eye are a very complex subject which has undergone a wide variety of studies for many years. It is unfortunate for the purpose of modeling that the eye is not a constant among individuals. The limiting resolution of the eye is very dynamic and varies with brightness, contrast, dark adaptation time, flicker rate, viewing time, color content, target movement, clutter, spatial and temporal noise, axial location of the target relative to the axis of the eye, and many other physiological conditions. Therefore, it should not be surprising that deviations from the model results may occur since this model considers only an average set of characteristics for the eyes. For the purpose of modeling the image intensifier system, the following conditions will apply:

- The target viewed is on the optical axis with the eye's fovea.
- The target is stationary.
- The target is not irradiated with a pulsed light source.

The primary eye parameters which affect performance are its MTF and sensitivity. Ian Overington[3] presents MTF of the refraction optics of the eye, MTF_o, which is prepared from data in Campbell and Gubisch.[4] The MTF of the optics varies with the eye's pupil diameter and may be approximated according to the following:

$$MTF_o = e^{-\left(\frac{f_r}{f_{co}}\right)^{1o}} \qquad (59)$$

where, f_r = the spatial frequency (cy/mm) on the retina

The MTF frequency constant, f_{co}, and the MTF index, i_o, are determined by the eye's pupil diameter, d, as shown in the following table:

Table 1. Eye's MTF Parameters vs Pupil Diameter

Pupil diameter d (mm)	Frequency constant f_{co} (cy/mm)	MTF index i_o
1.5	36	0.9
2	39	0.8
2.4	35	0.8
3	32	0.77
3.8	25	0.75
4.9	15	0.72
5.8	11	0.69
6.6	8	0.66

The effective focal length of the eye that will be used to relate retinal spatial frequency to the angular frequency is 22.89mm (re: MIL-HDBK-141). Therefore, angular resolution to the eye, R_e, is related to the retinal spatial frequency as follows:

$$R_e = \frac{f_r \times 22.89}{1000} \tag{60}$$

Figure 1 shows the MTF of the eye's optics, MTF_o, versus the angular frequency, R_e, for pupil sizes from 2mm to 6.6mm according to Equations 59 and 60.

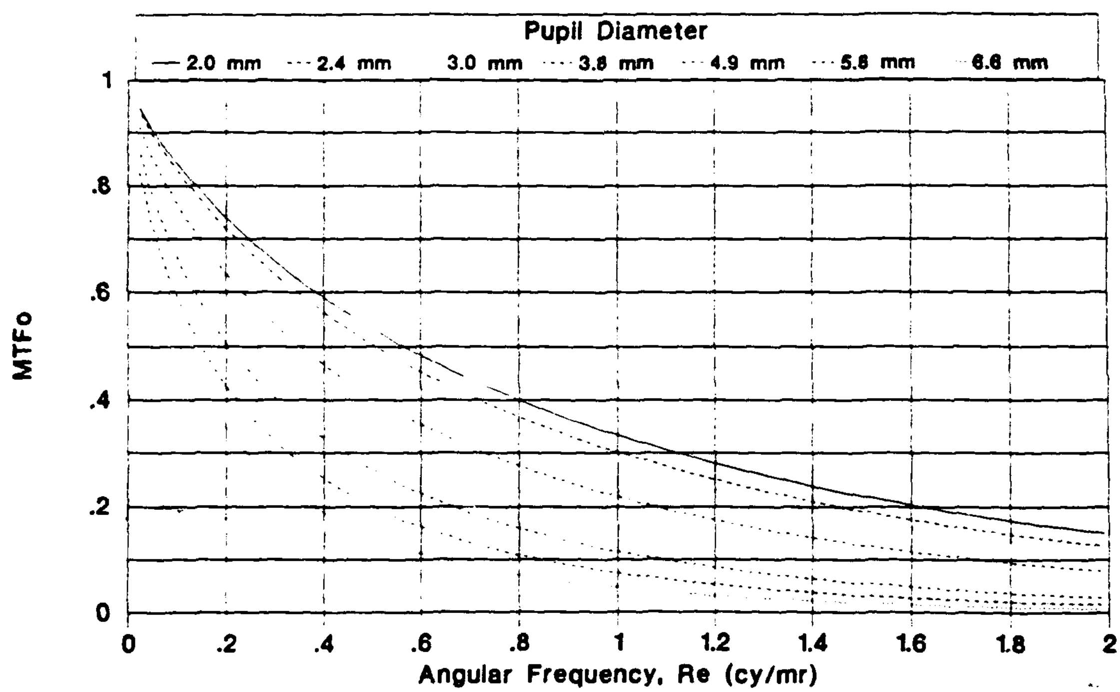

Figure 1. MTF of the Eye's Refraction Optics

In addition to the optics MTF, Overington also presents the MTF of the foveal retina which will be approximated by the following equation:

$$MTF_r = e^{-\frac{f_r}{130}} \tag{61}$$

Figure 2 shows the MTF of the foveal retina, MTF_r, versus the angular frequency, R_e, according to Equations 60 and 61. The product of the optic MTF in Figure 1 (Equation 59) with the foveal retina MTF of Figure 2 (Equation 61) will be the total MTF of the eye, MTF_e, as shown in Figure 3 and by the following equation:

$$MTF_e = e^{-\left(\frac{f_r}{f_{co}}\right)^{10}} \times e^{-\frac{f_r}{130}} \tag{62}$$

Since the MTF of the eye varies significantly with the diameter of the pupil, establishing the pupil diameter is essential to incorporate the eye into the overall system performance. Numerous measures of pupil diameter are in the literature.[3,4,5,6] It is assumed that the scene luminance uniformly covers an angular subtense to the eye(s) that follows the profile as presented in Figure 4 for this model. It is interesting to note that the diameter is decreased (MTF increased) when both eyes are illuminated. This will account for differences in the eye's MTF between monocular and bi(n)ocular viewing systems.

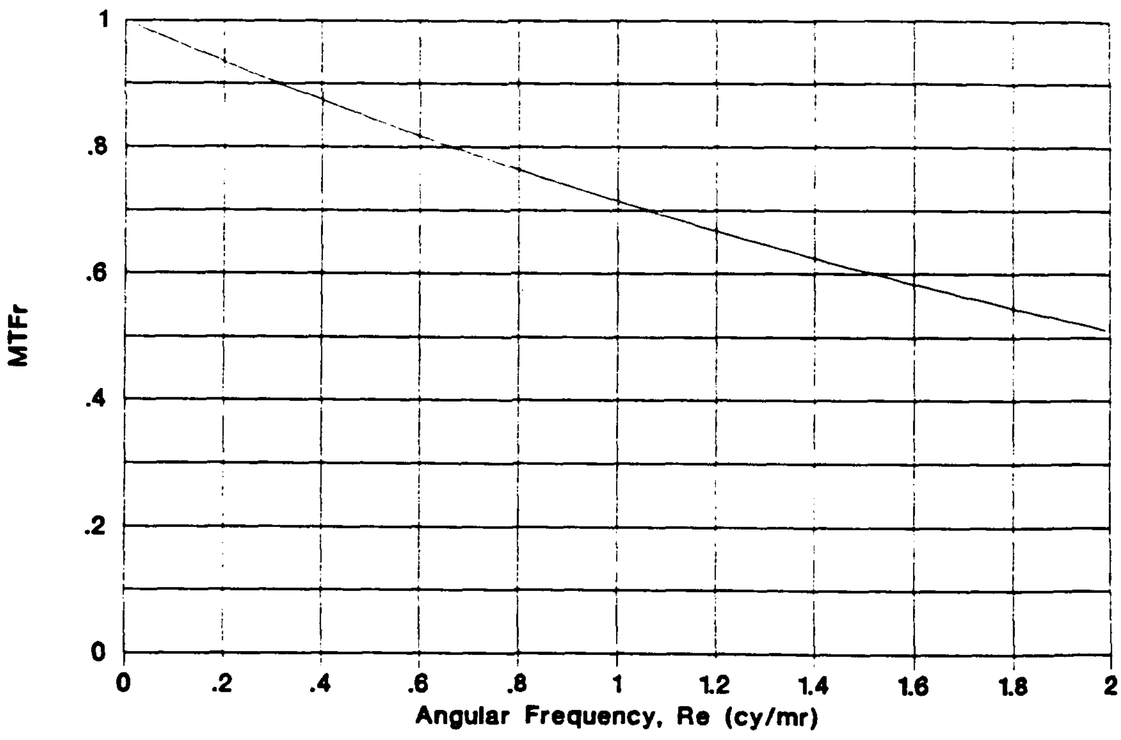

Figure 2. MTF of the Foveal Retina

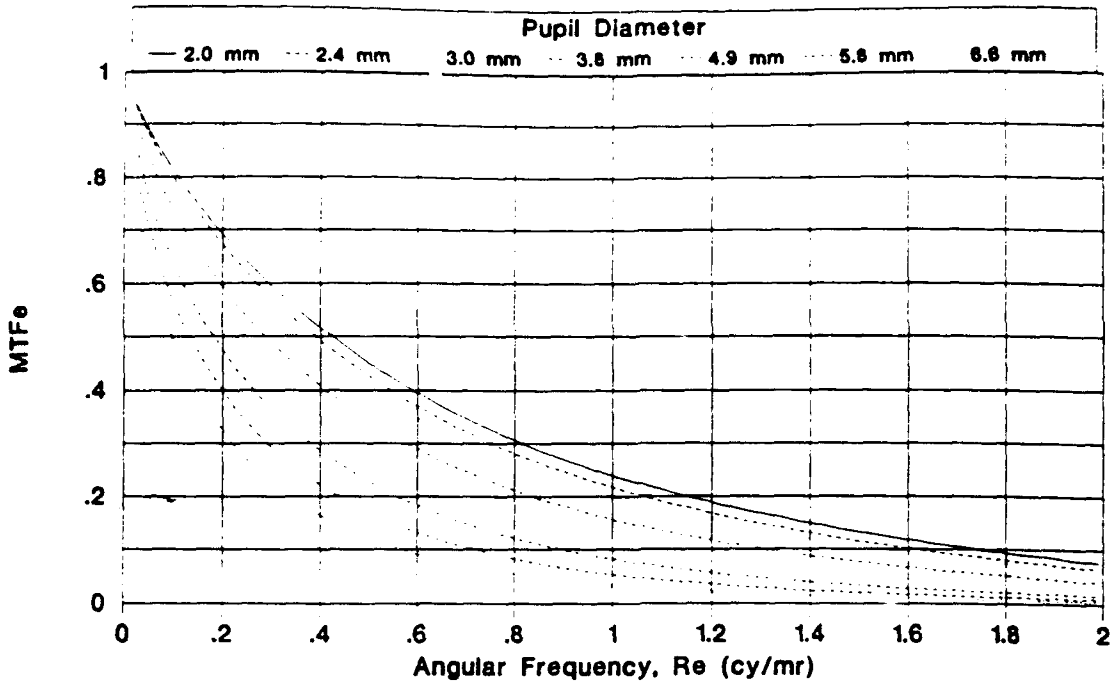

Figure 3. Total of MTF of the Eye

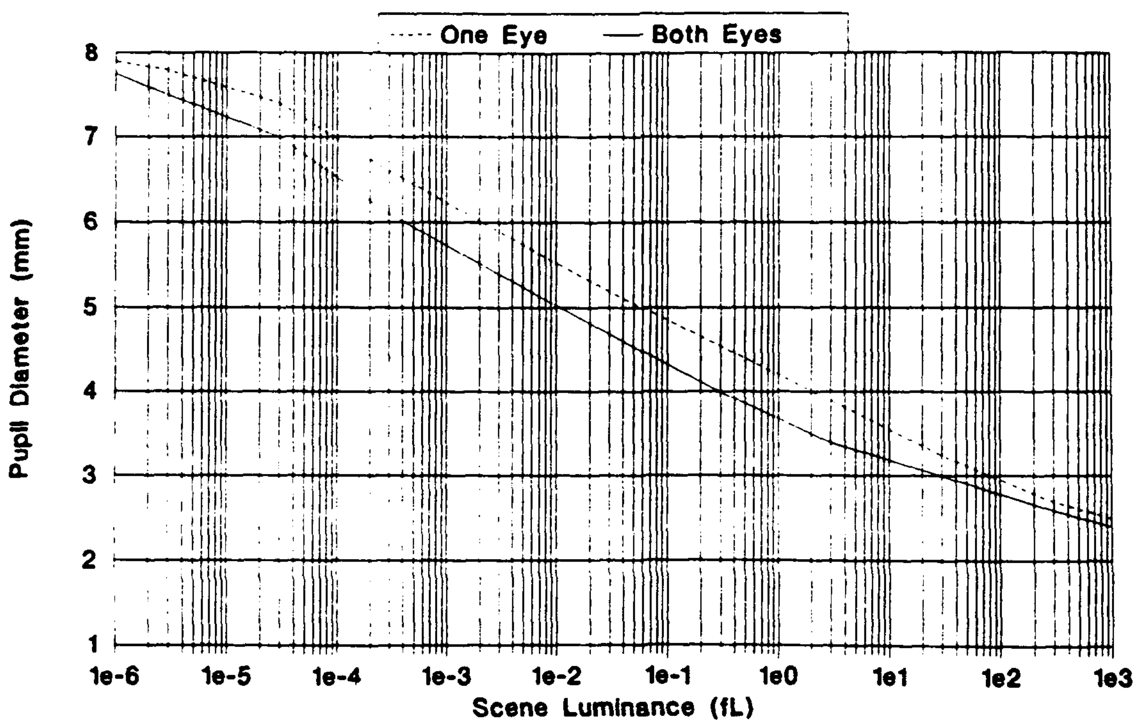

Figure 4. Pupil Diameter vs Scene Luminance

It will be assumed that the eye's signal-to-noise is 5.0 as quantified by the same methodology in measuring that of image intensifier tubes: 0.2mm spot diameter at 10^{-5} fC of 2856K blackbody distribution over a 10hz noise equivalent bandwidth.

If the intensifier model as derived earlier is valid, then it should also be valid for determining the resolution of the eye. Assuming that the eye has a negligible dark level (ie, EBI = 0), an appropriate starting point to generate the eye performance model is with Equation 13, repeated here for reference:

$$H = \left(\frac{26.8 \times R_c T_{no}}{881 \times EFL_i \times S/N_{out} \times K_f} \right)^2 \times \frac{1 + C_{out}}{C_{out}^2} \tag{63}$$

Some of the eye's parameters can readily be recognized:

$EFL_i = 22.89$ mm
$T_{no} = EFL_i/d = 22.89/d$

It is valid to let the T-number equal the F-number by attributing the loss of the optics transmittance to the loss in sensitivity or signal-to-noise at the retina. Since an intensifier system increases the brightness to the eye by its gain, G_s, the resultant signal-to-noise of the eye under this condition will be increased by the square root of G_s. Therefore,

$S/N_{out} = S/N_e \times G_s^{1/2}$, where $S/N_e = 5.0$

In addition to these substitutions, the K-factor, K_f, would have to be unity since all signal-to-noise measures are characterized over the same noise equivalent bandwidth of the eye: 10hz. The R_c term in Equation 63 relates to the spatial frequency at the fovea, f_r, whereas the original definition of R_c was the spatial frequency at the cathode image plane of the intensifier tube. Therefore, replacing R_c with f_r, and referencing the retinal spatial frequency to the cathode plane yields the following:

$$f_r = \frac{EFL_i \; R_c}{22.89 \; M} \tag{64}$$

The C_{out} term in Equation 63 relates to the resultant contrast at the fovea. This may be computed by combining (multiplying) the image tube MTF with that of the eye in Equations 22 to 25, 27 to 31, and 32 to 35. Tri-bar target contrast transfer is best approximated by using the CTF (Equation 25) as follows:

$$C_{out} = \frac{4\,C}{\pi} \left[MTF(f)\; MTF_e(f_r) - \frac{MTF(3f)\; MTF_e(3f_r)}{3} + \frac{MTF(5f)\; MTF_e(5f_r)}{5} - \ldots \right] \tag{65}$$

where,

C = the target's contrast

MTF(f) = the MTF of the intensifier tube (may also include that of the intensifier system optics)

$MTF_e(f_r)$ = the MTF of the eye where $f_r = EFL_i\, f/(22.89\ M)$

Expressing Equation 65 in an abbreviated format,

$$C_{out} = C \times \{ C_m \times C_{eye} \}$$

With these substitutions Equation 63 can now be reformulated for the eye as follows:

$$H_e = \left(\frac{26.8 \times EFL_i \times R_c}{881 \times 22.89 \times S/N_e \times \sqrt{G_s} \times M \times d} \right)^2 \times \frac{1 + C\{C_m \ C_{eye}\}}{(C\{C_m \ C_{eye}\})^2} \qquad (66)$$

where H_e is the required higher luminance level of either target or background amplified in brightness by G_s for the eye to resolve R_c lp/mm as referenced to the intensifier's cathode.

Equation 66 theoretically would represent a complete model for aided vision in which the intensifier system provides only a brightness gain to the eye; the intensifier tube's EBI would be zero, and its signal-to-noise would be infinite. However, because these intensifier parameters are finite, the required target brightness would have to be greater than H_e. Recall that the intensifier system's high light level solution was represented by Equation 17 and is repeated here for reference:

$$H_s = K_s^2 \times \frac{1 + C_e C_m}{(C_e C_m)^2} \qquad (67)$$

where the subscript "s" now refers to the intensifier system parameters to distinguish them from those of the eye. The resultant direct view model solution for the high light level, H, would be the sum of H_s (Equation 67) and H_e (Equation 66):

$$H = K_s^2 \times \frac{1 + C_e C_m}{(C_e C_m)^2} + K_e^2 \times \frac{1 + C_e\{C_m C_{eye}\}}{(C_e\{C_m C_{eye}\})^2} \qquad (68)$$

where,

$$K_s = \frac{26.8 \times R_c T_{no}}{881 \times EFL_i \times S/N_{out} \times K_f} \qquad (69)$$

$$K_e = \frac{26.8 \times EFL_i \times R_c}{881 \times 22.89 \times S/N_e \times \sqrt{G_s} \times M \times d} \qquad (70)$$

and according to Equation 16,

$$C_e = \frac{HC}{H + e(1 + C)} \qquad (71)$$

Recall that C_e accounts for the effective reduction in target contrast due to the image tube's EBI (see Equation 14), and must now replace the C term in Equation 66. The effort taken to provide a closed solution for H (see Equation 18) is possible here with the exception of having to iterate the results that determine the eye's pupil diameter, and subsequently the eye's MTF. Substituting Equation 71 into Equation 68 may be reduced to the following form:

$$H^3 - aH^2 - bH - c = 0 \tag{72}$$

where,

$$a = K_s^2 \frac{(1 + CC_m)}{(C\ C_m)^2} + K_e^2 \frac{(1 + C\ \{C_m C_{eye}\})}{(C\ \{C_m C_{eye}\})^2} \tag{73}$$

$$b = e(1 + C)\left(K_s^2 \frac{(2 + CC_m)}{(C\ C_m)^2} + K_e^2 \frac{(2 + C\ \{C_m C_{eye}\})}{(C\ \{C_m C_{eye}\})^2} \right) \tag{74}$$

$$c = e^2 (1 + C)^2 \left(\frac{K_s^2}{(C\ C_m)^2} + \frac{K_e^2}{(C\ \{C_m C_{eye}\})^2} \right) \tag{75}$$

The solution of the cubic Equation 72 for H gives the high light luminance level required to resolve a target having R_c lp/mm at the photocathode image plane. The system's angular resolution referenced to the input, and the angular resolution presented to the eye are described by Equations 19 and 20 respectively.

Gain Saturation Effect on Output Brightness

It is important to note that at the higher light levels the automatic brightness control (ABC) circuit within the image intensifier tube may limit the high light output brightness. The output brightness level of an image tube in its ABC mode is measured by uniformly illuminating the full photocathode area with white (2856K blackbody distribution) light at about 2×10^{-4} to 5×10^{-4} footcandles. A measure of the output brightness from the screen is often referred to as the "maximum output brightness". However, it is a maximum only when the full area of the photocathode is illuminated. If one half of the area were illuminated, then the output brightness would be double the "maximum output brightness". Very small areas of illumination could result in output brightness as high as 50 foot lamberts before the nonlinear gain due to local saturation begins to have an effect.

Assuming that the image intensifier system is operating in the linear gain region, the light level seen by the eye, L_e, is:

$$L_e = \frac{G\ t_e}{4\ T_{no}^2} \left[H \times G_r(R_c) + e \right] \tag{76}$$

where,

H = the high light luminance determined from Equation 72
G = the image intensifier tube's linear gain (fL/fC)
$G_r(R_c)$ = the gain reduction factor

t_e = the eyepiece transmittance (fL/fL)
T_{no} = the T-number of the input objective
e = EBI as referenced at the target (equation 14)

This equation is valid only for light level inputs that are within the linear gain region where the ABC circuit has negligible effect. At higher light levels the actual maximum output brightness is a function of the ABC setting, and on the total flux of irradiation on the photocathode (lumens), but not on the flux density (foot candles). This has a direct effect on the light level as seen by the eye in Equation 76. To account for higher levels of illumination, Equation 76 needs to be amended as follows:

$$L_e = \frac{G \times t_e}{4\ T_{no}^2}\left[H \times G_r(R_c) + e \right]\left[1 + \left(\frac{H_b \times G}{4\ T_{no}^2 \times L_{max}}\right)^4\right]^{-\frac{1}{4}} \tag{77}$$

where:

L_{max} = the image tube's maximum output brightness (fL)
H_b = H, if the background is brighter than the target
H_b = H x (1 - C)/(1 + C), if the target is brighter than the background
H_b = H/(1 + C), if the spatial shape is periodic

The H_b term corresponds to the background brightness (or average brightness for a periodic input) which comprises the greatest area of illumination at the photocathode. As a result the system gain, G_s, to be applied to Equation 70 is the output brightness to the eye divided by the target luminance (= L_e/H) which may be derived from Equation 77 as follows:

$$G_s = \frac{G \times t_e}{4\ T_{no}^2}\left[G_r(R_c) + \frac{e}{H} \right]\left[1 + \left(\frac{H_b \times G}{4\ T_{no}^2 \times L_{max}}\right)^4\right]^{-\frac{1}{4}} \tag{78}$$

where:

G = the image intensifier tube's linear gain (fL/fC)
$G_r(R_c)$ = the gain reduction factor
t_e = the eyepiece transmittance (fL/fL)
T_{no} = the T-number of the input objective
e = EBI as referenced at the target (Equation 14)
L_{max} = the image tube's maximum output brightness (fL)
H_b = H, if the background is brighter than the target
H_b = H x (1 - C)/(1 + C), if the target is brighter than the background
H_b = H/(1 + C), if the spatial shape is periodic

It will be assumed that the eye's pupil diameter, d, (Figure 4) is determined by the higher light level as seen by the eye (ie, G_s x H) inclusive of all spatial shapes under consideration. Recall that the pupil diameter, d, establishes the eye's MTF (Equations 59 to 62) and the eye's constant, K_e (Equation 70).

This model does not include conditions where the local saturation effect of the microchannel plate (due to a small area of illumination at the photocathode at a very high light input) is a factor. This condition may be present at photocathode illumination levels above 1×10^{-3} fC. The

effect of local saturation is that it not only limits output brightness to a greater degree than expressed in Equation 78, but it also reduces the image contrast at the tube's output -- i.e., the image tube's MTF degrades under this condition.

Monocular, Binocular, and Biocular Systems

The set of equations thus far provide a means to characterize system performance in a straight forward manner for monocular viewing. However, binocular and biocular systems present other considerations that require additional computations. For example, what is the effect of a binocular system with different image tube parameters (gain, EBI, MTF, signal-to-noise) for the left and right channels? The brain processes the images from each eye to yield a single interpretation of the object being viewed. The following discussion presents a theoretical approach for combining the two images.

The effects of binocular/monocular viewing as discussed by Overington suggests that a person having two equally good eyes being used as nature intended (same stimulus presented to both) will have a visual threshold performance improvement by a factor of the square root of two. This implies that the brain sums the two images in quadrature to yield a single interpretation of that image. This presents an interesting effect considering that each eye observes two different images in binocular intensifier systems, but the same image in biocular systems. For intensifier-aided vision the effects will be separated into spatial enhancement and temporal enhancement.

The binocular improvement in visual threshold as discussed by Overington is a spatial enhancement. It will be assumed that this enhancement is in the form of improved MTF when both eyes are used. Specifically it is assumed that the limiting resolution for two channel viewing is the quadrature sum of the limiting resolution for each channel:

$$R_L = \sqrt{R_{L\,(left)}^2 + R_{L\,(right)}^2} \tag{79}$$

where R_L = the limiting resolution of the intensifier tube

This improvement is assumed to be present for both binocular and biocular systems. Also this improvement is most noticeable at the higher light levels where the limiting resolution of the system approaches the limiting resolution of the intensifier tube.

The temporal enhancement is assumed to be a quadrature summation of the signal-to-noise of each intensifier tube in binocular systems where the signal-to-noise of each channel is independent:

$$S/N_{out} = \sqrt{S/N_{out\,(left)}^2 + S/N_{out\,(right)}^2} \tag{80}$$

where S/N_{out} = the signal-to-noise of the intensifier tube

It is assumed that no temporal enhancement is attained with biocular systems since both eyes see the same signal and noise from the one image tube.

The theoretical implication of these two effects is that parallel channel viewing (binocular and biocular) yields a single high light solution that is equal to the product over sum of the individual high light solutions for each channel (Equation 68) with the following substitutions:

a. The MTF of each channel, binocular and biocular, is increased by the result of an increase in the limiting resolution according to Equation 79. The resultant MTF can be calculated by referring to Equation 85 and the section titled "Special Considerations" which follows later.

b. If the system is a binocular type, then solve for H (the high light level) for the left channel where S/N_{out} in Equation 69 is the left intensifier's signal-to-noise. Likewise solve for H for the right channel where S/N_{out} in Equation 69 is the right intensifier's signal-to-noise.

c. If the system is a biocular type, then solve for H using 'a' and 'b' above with the exception of entering $S/N_{out}/\sqrt{2}$ for both left and right channel solutions. This assumed split in the signal-to-noise is due to the fact that both eyes see correlated noise from the one image tube. The subsequent eye/brain summation of the two channels yields a quadrature summation that results in a signal-to-noise to the brain equal to the S/N_{out} from the one image.

d. The eye's pupil diameter follows the "Both Eyes" function in Figure 4 which determines the eye's MTF and is also a parameter in Equation 70. The scene luminance is assumed to be the average of the high light levels (G_s x H) computed for each eye.

The two solutions, one for each eye, result in a value for the left eye (H_{left}), and a value for the right eye (H_{right}). The single solution for the required high light level is:

$$H = \frac{H_{left}\ H_{right}}{H_{left} + H_{right}} \tag{81}$$

Verification of these assumptions, and the model as a whole for that matter, will be validated later with numerous examples of actual observer data compared to the model predictions.

Model Flow Chart Summary

The flow chart on the following pages summarizes the sequence and relevant modeling equations to be used. The reference letters a-f in the chart refer to the corresponding paragraph in the "Special Considerations" section following the flow chart.

Reference letters (a) to (f) refer to considerations which follow.

PROCESS	VARIABLE	PARAMETER/VALUE	UNITS	EQN
(1) INPUT conditions[f]	shape C T	spatial shape/ **p** if periodic **sp** if single positive **sn** if single negative **3p** if tri-bar positive **3n** if tri-bar negative contrast temperature	 - - - - - - °C	 2
(2) INPUT image tube parameters	Gen form type S/N_{out} EBI $G^{(e)}$ $L_{max}^{(b)}$ R_L	generation/ **2** or **3** format/ **18** or **25** monocular/ = **mon** binocular/ = **bin** biocular/ = **bio** signal-to-noise equivalent brightness input linear gain maximum output brightness limiting resolution(s)	- mm - - - - L/cm^2 fL/fC fL lp/mm	
(3) COMPUTE	R_L $MTF(f)^{(a)}$ S/N_{out}	limiting resolution/ $[R_{L(left)}{}^2+R_{L(right)}{}^2]^{1/2}$ if type = bin or bio modulation transfer function signal-to-noise/ $= 0.707 \times S/N_{out}$ if type = bio	 lp/mm - -	 79 85
(4) SET	K_f	K-factor/ **1.24** if Gen=2, form=18 or RCA 1052 phosphor **1.3** if Gen=2, form=25 or P1/P39 phosphor **1.19** if Gen=3 or P-20 phosphor	- - -	
(5) SET	T_c	Temp. coefficient/ 3 if Gen = 2 4 if Gen = 3	°C °C	
(6) INPUT system parameters[d]	EFL_i T_{no} M $t_e^{(c)}$	input optic EFL input optic T-number system magnification eyepiece transmittance	mm - - fL/fL	
(7) COMPUTE	e	EBI @ target	fL	14

PROCESS	VARIABLE	PARAMETER/VALUE	UNITS	EQN
(8) INITIALIZE	R_c	frequency @ image plane/ set to 1	lp/mm	
(9) COMPUTE	CTF(f)	contrast transfer function/ $\mathbf{CTF(R_c)}$ if shape = p, 3p or 3n	-	25
(10) COMPUTE	$H_s(\tau)$	Fourier integral/ $\mathbf{H_s(1/2R_c)}$ if shape = sp or sn	-	27
(11) COMPUTE	C_m	contrast transfer of image tube/ $\mathbf{CTF(R_c)}$ if shape = p (EQN 31) if shape = sp (EQN 35) if shape = sn $\mathbf{H_{3p}(R_c)}$ if shape = 3p $\mathbf{H_{3n}(R_c)}$ if shape = 3n	 - - - - -	 25 31 35 36 38
(12) COMPUTE	K_s CC_m	system constant system output contrast	 fL	 69
(13) COMPUTE	$G_r(R_c)$	gain reduction factor/ (EQN 45) if shape = p (EQN 48) if shape = sp 1 if shape = sn (EQN 53) if shape = 3p 1 if shape = 3n	 - - - - -	 45 48 53
(14) INITIALIZE	d f_{co} i_o H_b	pupil diameter/ di = **6.6** freq. constant/ = **8** MTF index/ = **0.66** background brightness/= **0**	mm lp/mm - fL	
(15) COMPUTE	f_r MTF_e G_s K_e CC_mC_{eye} a b c	foveal spatial freq. eye's MTF system gain eye constant contrast at retina cubic equation constant cubic equation constant cubic equation constant	lp/mm - fL/fL fL - - - -	64 62 78 70 65 73 74 75
(16) SOLVE	H	high light target luminance required	fL	72

PROCESS	VARIABLE	PARAMETER/VALUE	UNITS	EQN
(17) COMPUTE	H_b	background brightness/ H/(1+C) if shape = p	fL	
		H if shape = sn or 3n	fL	
		H x (1-C)/(1+C) if shape = sp or 3p	fL	
(18) COMPUTE	L_e	brightness to the eye		77
(19) LOOK-UP	d	eye's pupil diameter from Fig. 4	mm	
(20) COMPARE	d with d_i	eye's pupil diameter, if $\mid d - d_i \mid < 0.1$ GOTO (24)	mm	
(21) SET	d_i	eye's pupil diameter/ = d	mm	
(22) INTER-POLATE	f_{co} i_o	eye's frequency constant eye's MTF index (both from Table 1)	lp/mm	
(23) ITERATE		GOTO (15)		
(24) COMPUTE (STORE)	R_i	system input resolution at H fL	cy/mr	19
(25) INCRE-MENT	R_c	let Rc = Rc + 1, GOTO (9) [do this up to the max frequency of interest]	lp/mm	
(26) REPEAT		if type = bin or bio, repeat (2) to (25) for the second channel, then GOTO (27) else GOTO (28)		
(27) COMPUTE	H	$H = (H_{left}^{-1} + H_{right}^{-1})^{-1}$		81
(28) Plot the set of points (H,R_i) determined at each increment of R_c				

(a) Image Tube MTF

The MTF of image intensifier tubes has been described under a variety of formats: the MIL-SPEC method of specifying MTF at four spatial frequencies (2.5, 7.5, 15, and 25 lp/mm), multiple-point MTF at selected increments, and quite often the MTF is unknown. None of these formats are sufficient for modeling intensifier system performance. One must resort to interpolations and/or extrapolations to describe the full MTF function. This is necessary especially since presently produced and future image tubes[7] exhibit a resolution limit well beyond the MIL-SPEC's 25 lp/mm maximum specified measurement point. However, the following analytical approximation for image intensifier tube MTF, formulated by Johnson,[8] can be employed to overcome this limitation:

$$MTF(f) = e^{-\left(\frac{f}{f_c}\right)^i} \tag{82}$$

where,

f_c = the MTF frequency constant
i = the MTF index limited to the region: $1 < i < 2$

The constants fc and i can be determined by a "best fit" approximation to a set of measured MTF data. If no MTF values are available, but the limiting resolution (R_L lp/mm) is known, then MTF(f) can be approximated using Equation 82 as follows:

Assume that the limiting resolution, R_L, corresponds to a contrast of 1.5% [realize the convention of expressing contrast is still (High - Low)/(High + Low)]. This value of resolution is normally measured with a 100% contrast tri-bar target, black bars on a white background. Therefore, $H_{3n}(R_L) = .015$ according to Equation 38. It can be shown that the corresponding MTF at R_L cy/mm would have to be 4.5% [ie, $MTF(R_L) = .045$]. These values are also evident in the table which follows Equation 38.

With this assumption the MTF frequency constant, f_c, can be determined from Equation 82 as follows:

$$.045 = e^{-\left(\frac{R_L}{f_c}\right)^i} \tag{83}$$

Solving Equation 83 for f_c yields:

$$f_c = \frac{R_L}{\{-\ln(.045)\}^{1/i}} \approx \frac{R_L}{3.101^{1/i}} \tag{84}$$

Therefore, the MTF may be approximated as:

$$MTF(f) \approx e^{-\left(\frac{3.101^{1/i} f}{R_L}\right)^i} = e^{-3.101\left(\frac{f}{R_L}\right)^i} \tag{85}$$

where R_L = the image tube's limiting resolution, and typically $1.2 < i < 1.5$ for image intensifier tubes

(b) Maximum Output Brightness

When modeling the resolution limit of an image intensifier system, the prediction often falls short of actual high light level resolution measures. The reason is that during actual measures of limiting resolution, only a small region, typically about two percent, of the photocathode area is illuminated. This condition allows the output brightness from the intensifier tube to exceed the automatic brightness control (ABC) setting which is typically 1 fL for the 18mm tubes, and 6 fL for the 25mm tubes. Therefore, the actual maximum output brightness during the resolution measure may be as high as 50 fL. Setting L_{max} in Equation 62 to 50 fL will provide a more accurate representation of the resolution test condition, and will result in a higher system resolution, but only at the higher light levels. Low light resolution in the linear gain region of the intensifier tube will not be affected.

(c) Magnification Within the Image Tube

Some image intensifier systems are designed with magnifying image tubes. For example, the AN/VVS-2 Driver's Viewer has a 25/46 fiber optic (FO) expander optically coupled to the 25mm image tube's output. The image tube's parameters are separately characterized — they do not account for losses impose by the expander. Therefore, from a modeling perspective this system design imposes intuitive c· ısiderations by the modeler. One approach is to consider the FO expander as part of the eye iece. Since the FO expander's transmittance is 0.3, it would be reasonable to multiply the ϲyepiece transmittance, t_e, by 0.3 and enter the result as t_e in the modeling equations (ref: Equations 76 to 78). Assuming no loss in MTF, this is all that need be done to incorporate the effect of the FO expander.

(d) MTF and Image Tube/System Magnification

This version of the model relies on all parameters being referenced to the photocathode image plane. Therefore, the general rule is to reference all spatial frequencies for MTF measures to that image plane. Provided that the MTF of all components (input optic, image tube, FO expander, eyepiece, etc.) is scaled to the cathode plane, then the system MTF would be the product of the individual component MTFs. This resultant product of the MTFs may then be regarded as the MTF to be used in Equations 22 to 39.

(e) Image Tube Gain

Image tube gain is measured with uniform illumination on the full active area of the photocathode, and average output brightness of nearly the full active area. Since the allowable output brightness uniformity is 3/1, and since the central area is invariably the brighter region, the actual image tube gain on-axis is typically 20 percent (may range 40 percent) higher than measured. Therefore, it may be necessary or desirable to account for this detail by increasing the reported image tube gain by a factor of at least 1.2 in the modeling Equations 40 and 76 to 78.

(f) Spectral Considerations

Since all image tube parameters are quantified with light sources exhibiting a 2856K blackbody distribution throughout the spectral region of interest (400nm to 1000 nm), this version of the model is applicable for only 2856K type sources. The resolution target radiance, therefore, must present this type of spectral shape. This requires that the spectral reflectivity (or transmittance of back-illuminated targets) be constant throughout the spectral region of interest if the light source were set to 2856K. However, this criteria does not limit the model's applicability to field environment conditions. Certainly a given set of field conditions (spectral irradiance, atmospheric spectral transmittance and scatter, target and background spectral reflectivity) establish a quantifiable contrast within the spectral band of the intensifier system, and additionally an equivalent light level having a 2856K blackbody distribution.

The reader is referred to a planned update of the NVESD Image Intensifier Performance Model to be released in early calendar year 1994. The revised performance model will include this work on limiting resolution and establish the link between limiting resolution and the traditional Minimum Resolvable Contrast utilized for the prediction of observer performance in field conditions.

References

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8. Johnson, C. B., "Point-Spread Functions, Line-Spread Functions, and Edge-Response Functions Associated with MTFs of the Form $\exp[-(\omega/\omega_c)^n]$," *Applied Optics*, Volume 12, No.5, pg.1031, 1973.

Symbology

CONSTANTS

Δf	= 10 hertz	Noise equivalent bandwidth of the eye and the intensifier tube's signal-to-noise measure
k	= 2	Threshold signal-to-noise for 50% probability of detection
K_f	= 1.24 for RCA 1052 = 1.19 for P-20 = 1.30 for P1/P39	Phosphor K-factor
q	= 1.602 x 10-19 coulomb	Elementary charge
S/N_e	= 5.0	Signal-to-noise of the Eye
t	= 0.2 second	Eye integration time
T_c	= 3 °C for 2nd Gen = 4 °C for 3rd Gen	Temperature coefficient of EBI

ABBREVIATIONS & UNITS OF MEASURE

ABC	Automatic brightness control
°C	Degrees centigrade
CCD	Charge coupled device
cm	Centimeter
cy	Cycle
EBI	Equivalent brightness input
fC	Footcandle
fL	Footlambert
FO	Fiber optic
freq	Spatial frequency
ft	Foot
Gen	Generation
hz	Hertz (cy/sec)
ln	Natural logarithm
lp	Line pair
MCP	Microchannel plate
mm	Millimeter
mr	Milliradian

MTF	Modulation transfer function
sec	Second

VARIABLES [units of measure]

A_o	Relative aperture of the input objective
C	Contrast at the target, (high - low)/(high + low), as viewed by the image intensifier system input
C_b	Contrast of target, $(L_o - L_s)/L_o$
C_e	Contrast at the target reduced by the effect of EBI
C_{eye}	Eye's contrast transfer
CF	Correction factor applied to the measured signal-to-noise value
C_m	Image tube's contrast transfer
C_{out}	Image tube's output image contrast
CTF(f)	Contrast transfer function
d	Pupil diameter of the eye, [mm]
e	Equivalent brightness input as referenced at the target due to the image intensifier tube's EBI, [fL]
EBI	Equivalent background input of image intensifier tube, [Lumen/cm^2]
EFL_i	Effective focal length of input optic, [mm]
f	Sinusoidal spatial frequency, [cy/mm]
F(nf)	Fourier series components of a periodic square wave
f_c	MTF frequency constant, [cy/mm]
f_{co}	MTF frequency constant of eye's optics, [cy/mm]
F_{no}	Input optic F-number
f_r	Spatial frequency at the eye's retina, [cy/mm]
G	Image intensifier tube gain, [fL/fC]
$G_r(R_c)$	Gain reduction factor of the image intensifier tube
G_{r1}	Approximate gain reduction factor for a 100% contrast tri-bar target, white on black
G_{r2}	Approximate gain reduction factor for a 100% contrast tri-bar target, black on white
G_s	System gain, [fL/fL]
H	Higher luminance level of either target or background, [fL]
$H_{3n}(f)$	Approximate contrast transfer of a tri-bar target, black on white
$H_{3p}(f)$	Approximate contrast transfer of a tri-bar target, white on black

H_b Background brightness (or average brightness for periodic spatial targets). [fL]

H_e Higher luminance level of target or background for eye to resolve target, [fL]

$H_i(R_c)$ The high light input at R_c lp/mm on the cathode. [fC]

H_{out} The higher brightness output of either target or background, [fL]

$H_p(f)$ The high light output due to a 100% contrast periodic square wave input at f lp/mm on the cathode with image intensifier tube gain normalized to 1

H_s Higher luminance level of target or background for intensifier system to resolve target, [fL]

$H_s(\tau)$ The high light output due to a 100% contrast singular positive bar target input of width τ mm on the cathode with image intensifier tube gain normalized to 1

i MTF index

I Average cathode current

i_o MTF index of eye's optics

K Substitution variable for $26.8\ R_c\ T_{no}/(881\ EFL_i\ S/N_{out}\ K_f)$

K_e Eye constant = $26.8\ EFL_i\ R_c/(881 \times 22.89\ S/N_e\ G_s^{1/2}\ M\ d)$

K_s System constant = K

L The lower luminance level of either target or background, [fL]

L_e The higher luminance of either target or background as viewed at the intensifier system's output, [fL]

L_{max} Maximum output brightness of the image tube, [fL]

L_o The higher target luminance as defined by Richards

L_{out} The lower output luminance of either target or background, [FL]

$L_p(f)$ The low light output due to a 100% contrast periodic square wave input at f lp/mm on the cathode with image intensifier tube gain normalized to 1

L_s The lower target luminance as defined by Richards

M Image intensifier system magnification

MTF(f) Modulation transfer function of image intensifier tube

MTF_e Total MTF of the eye

MTF_o MTF of the eye's optics

MTF_r MTF of the eye's foveal retina

n Integer value of Fourier series component

R_c The spatial frequency at the input photosurface of the image tube resolvable at the phosphor screen, [lp/mm]

R_e Angular resolution presented to the eye, [cy/mr]

R_i	Input angular resolution of intensifier system, [cy/mr]
R_L	The maximum or limiting spatial resolution of image intensifier tube, [lp/mm]
R_p	Spatial resolution at the input photosurface, limited by photon noise defined by Richards, [lp/unit length]
R_s	The angular resolution presented to the eye, [cy/mr]
S	Integral sensitivity of photocathode, [microamp per lumen]
S/N_{in}	Input signal-to-noise referenced to the photocathode over a 10 hertz noise equivalent bandwidth
S/N_{out}	The measured high light (1×10^{-5} fC) signal-to-noise of the image intensifier tube
S/N_s	The intensifier system's signal-to-noise
T	Ambient temperature, [°C]
t_e	Intensifier system's eyepiece transmittance, [fL/fL]
T_{no}	Image intensifier system's input optic T-number
t_T	Image intensifier system's input optic transmittance
τ	Spatial width of singular bar target, [mm]

Appendix A
Examples

Suitability of any analytical model is entirely dependent on how well the model prediction fits the actual measured data under real conditions. The primary intent of initially formulating this laboratory version of the model considered the following premise: **If an image intensifier model cannot accurately predict laboratory measured performance (where all test conditions and parameters are controlled and known), then it cannot be viable for predicting field performance (where conditions cannot be controlled nor are well known).**

The following examples present modeled results compared to observer data that had been collected on a variety of systems dating back to the early 80's and as recent as late 1992 at NVESD. These examples serve as a means to validate the modeling equations presented in this version of the image intensifier performance model. All image tube parameters presented for each image tube were measured at the NVESD Image Intensifier Measurement Facility in the Image Intensifier Tube Technology Team. All targets used were tri-bar types, USAF resolution charts, black bars on a white background. The targets were back-illuminated for all systems tested. This method of illumination retains color temperature of the source by eliminating the likelihood of reflectance from the black bars at the longer wavelengths of interest that would occur with front illumination.

The data input for each modeled condition is shown on the lower half of each system tested. Data input parameters are coded with a colon (:) after the parameter name. Other parameters are calculated from the inputs and are coded with an equal sign (=). Only one low contrast measure was available to analyze which is the second example where the target contrast was -45%. All other examples used -100% contrast targets. The image tube parameter inputs include the following:

TUBE PARAMETER	MEANING
n	MTF index of image tube (see Equation 85)
Lim Res	Limiting resolution, R_L
GEN	Image tube generation
FORMAT	Image tube format or cathode diameter
S/N(HL)	Image tube signal-to-noise output, S/N_{out}
GAIN	Image tube linear gain, G
EBI@21C	Image tube EBI at 21°C
TEMP(C)	Ambient temperature during test (°C)
Satur	Image tube maximum output brightness dictated by the tube's measured maximum output brightness (L_{max}) and the ratio of image area to cathode area (see paragraph 'b' under "Special Considerations").

The optics input parameters include the following:

OPTICS PARAMETER	MEANING
fc, n	Input optic frequency constant & MTF index
T-no	Input optic T-number
FOV	System optic's field-of-view
T-EYEPC	Eyepiece transmittance
EFL in	Input optic effective focal length
EFL out	Eyepiece effective focal length
CONTRAST	Target contrast where C = |CONTRAST|

The optic's MTF was determined to be well-characterized by Equation 82 as discussed by Johnson[8]. Although not displayed on the charts, the eyepiece MTF parameters used were: fc = 200, n = 1 for all systems except the AN/PVS-7's which used fc = 115, n = 1.

The calculated results were computed as follows:

Kf — Phosphor K-factor
= 1.24 for RCA 1052 (Gen 2, 18mm)
= 1.19 for P-20 (Gen 3)

Nf * — Image tube's MCP noise figure
= 1.54 if Gen 2 18mm
= 1.90 if Gen 3

Tcoeff — Temperature coefficient of EBI
= 3 if Gen 2
= 4 if Gen 3

SENS * — Photocathode sensitivity
$= (Nf \times S/N_{out} / 1.03)^2$

distor * — Input optic linear distortion

$$= \left[1 - \frac{Tan\left(\frac{.5 \times FORMAT}{EFL\ in}\right)}{Tan\left(\frac{.5 \times \pi \times FOV}{180}\right)} \right] \times 100\%$$

MAG — System magnification = (EFL in)/(EFL out)

SysGain — System's linear gain, G_s
$= 0.25 \times GAIN \times T\text{-}EYEPC / T\text{-}NO^2$

The asterisk (*) above denotes those computed parameters that are calculated for information only and do not enter into the performance model computations.

Data input for two channel systems uses a slash (/) to separate the left channel parameter from the right. To distinguish binocular from biocular systems, only one value for signal-to-noise is entered for biocular systems.

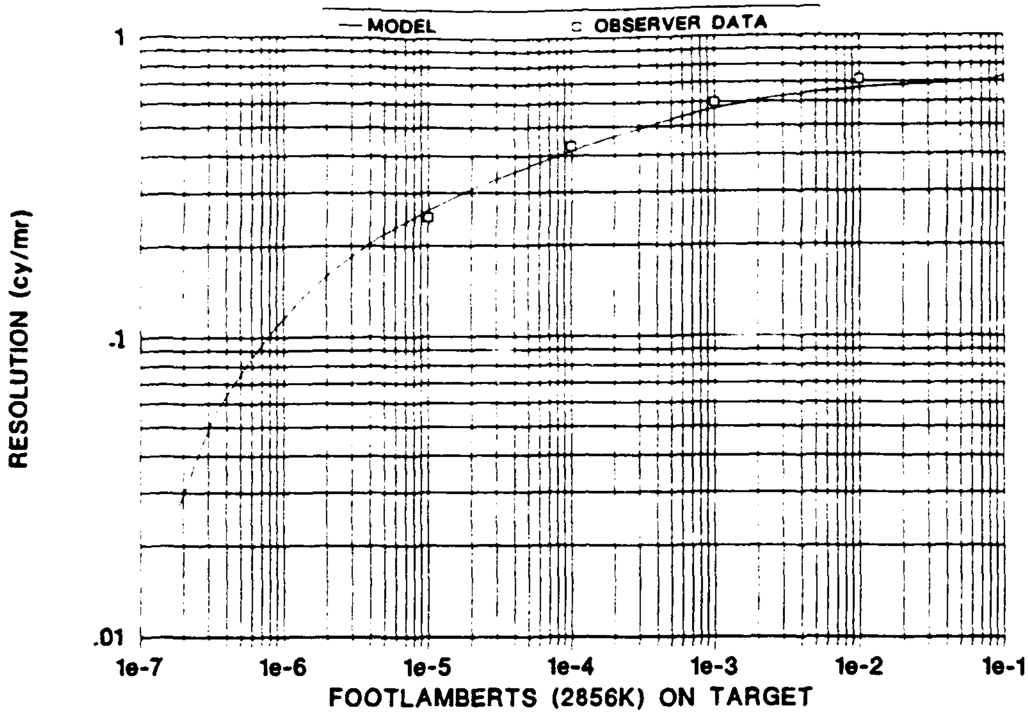
The bottom part of each printout shows the modeled results of resolution (Resol) at discrete light levels (LL) interpolated from the incremental solutions. The complete resolution vs light level curve is shown on the plot which compares the modeled results with the discrete observer data.

The table below categorizes the twenty system examples that follow.

CONFIGURATION	TYPE	GEN	MAGNIFICATION	PAGE
Monocular (6 ea)	AN/PVS-5A	2	1X	A-4 A-5
	AN/PVS-5C	2	1X	A-6
	AN/AVS-6	3	1X	A-7 A-8 A-9
Binocular (7 ea)	AN/PVS-5A	2	1X	A-10 A-11
	AN/PVS-5C	2	1X	A-12
	AN/AVS-6	3	1X	A-13 A-14 A-15 A-16
Biocular (3 ea)	AN/PVS-7A	3	1X	A-17
	AN/PVS-7B	3	1X	A-18 A-19
Monocular (4 ea)	3.6X Weapon Sight	3	3.6X	A-20
	4X Weapon Sight	2	4X	A-21
	4.3X Weapon Sight	3	4.3X	A-22
	6X Weapon Sight	3	6X	A-23

AN/PVS-5A Monocular Assembly

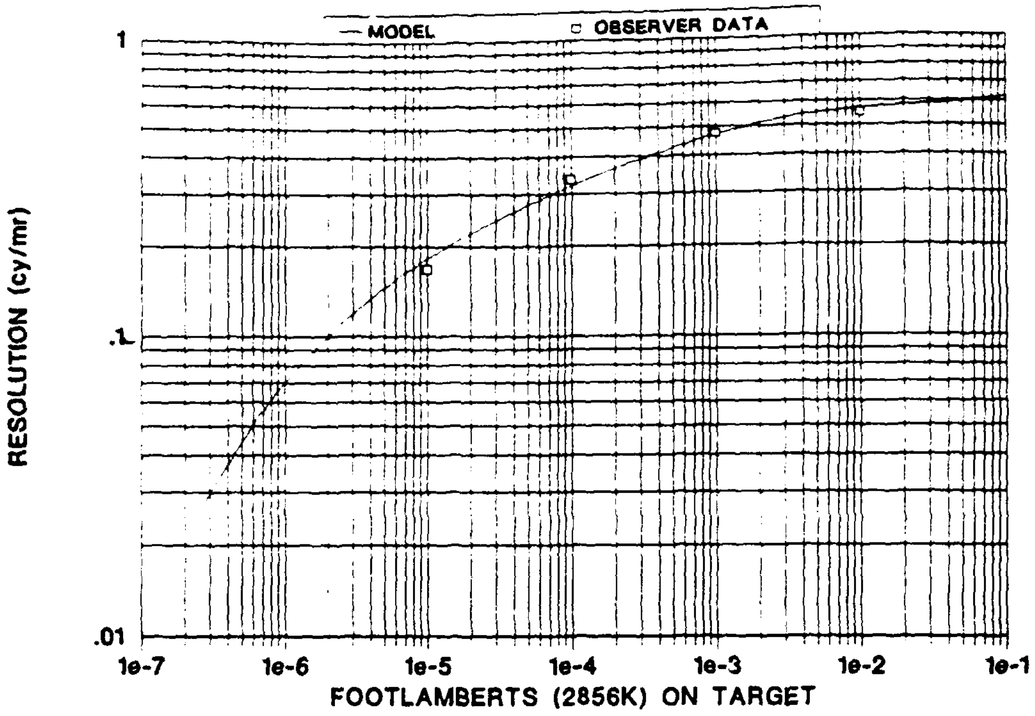
Image Tube Serial no. 5500



TUBE PARAMETERS:				OPTICS PARAMETERS:	
n:	1.25			fc, n:	45 1
Lim Res:	36 Lp/mm			distor =	4.9 %
GEN:	2			T-no:	1.61
FORMAT:	18 mm			FOV:	40 deg
S/N(HL):	14.88			MAG =	1
GAIN:	20000 FL/FC			T-EYEPC:	.8
EBI@21C:	1.75 E-11L/cm^2				
TEMP(C):	21 deg C				
Kf =	1.24			EFL in:	27 mm
Nf =	1.54			EFL out:	27 mm
Tcoeff =	3 deg C			CONTRAST:	-1
SENS =	495 uA/L			(T-B)/(T+B)	
Satur:	4 FL			SysGain =	1543.
At LL =	1e-2 FL,	Resol	=	.664 cy/mr	
=	1e-3 FL,		=	.570 cy/mr	
=	1e-4 FL,		=	.415 cy/mr	
=	1e-5 FL,		=	.264 cy/mr	

AN/PVS-5A Monocular Assembly

Image Tube Serial no. 5500

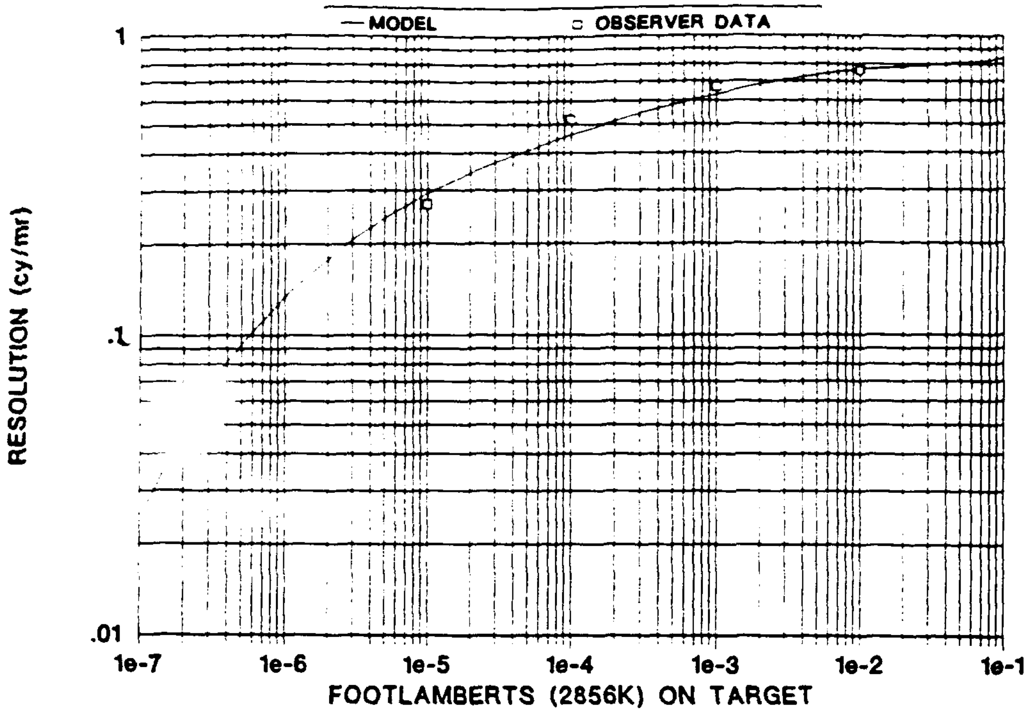


TUBE PARAMETERS:		OPTICS PARAMETERS:	
n:	1.25	fc, n:	45 1
Lim Res:	36 Lp/mm	distor =	4.9 %
GEN:	2	T-no:	1.61
FORMAT:	18 mm	FOV:	40 deg
S/N(HL):	14.88	MAG =	1
GAIN:	20000 FL/FC	T-EYEPC:	.8
EBI@21C:	1.75 E-11L/cm^2		
TEMP(C):	21 deg C		
Kf =	1.24	EFL in:	27 mm
Nf =	1.54	EFL out:	27 mm
Tcoeff =	3 deg C	CONTRAST:	-.45
SENS =	495 uA/L		(T-B)/(T+B)
Satur:	4 FL	SysGain =	1543.

At LL =	1e-2 FL,	Resol =	.566 cy/mr
=	1e-3 FL,	=	.470 cy/mr
=	1e-4 FL,	=	.321 cy/mr
=	1e-5 FL,	=	.183 cy/mr

AN/PVS-5C Monocular Assembly

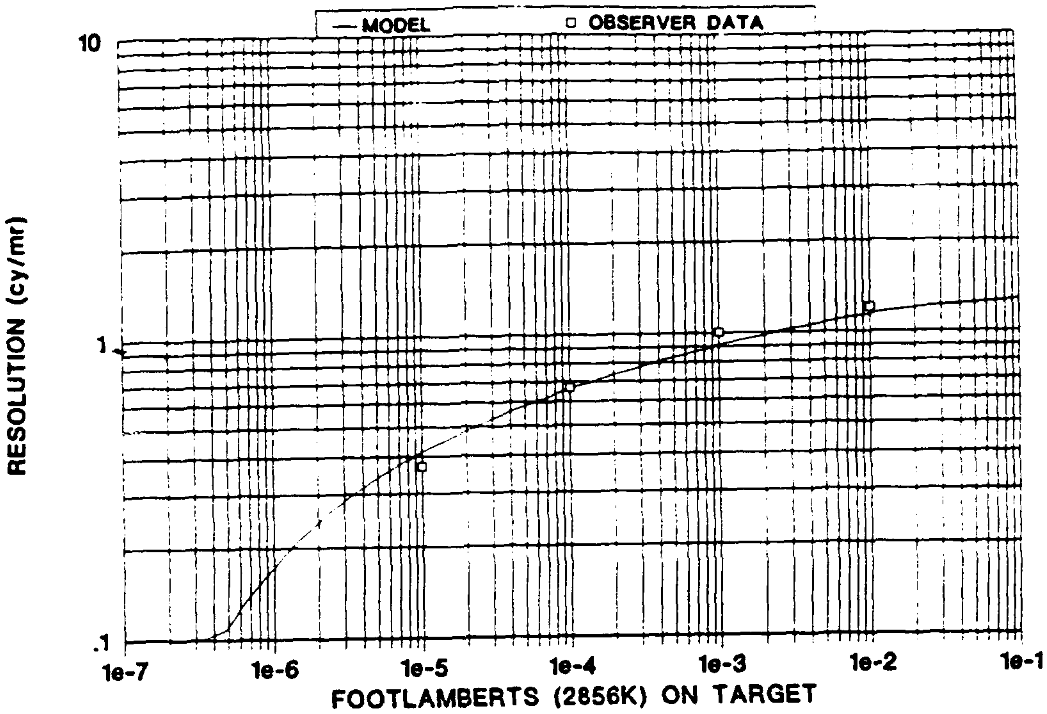
Image Tube Serial no. 279977



TUBE PARAMETERS:		OPTICS PARAMETERS:	
n:	1.4	fc, n:	75 1.7
Lim Res:	36 Lp/mm	distor =	4.9 %
GEN:	2	T-no:	1.3
FORMAT:	18 mm	FOV:	40 deg
S/N(HL):	11.51	MAG =	1
GAIN:	10750 FL/FC	T-EYEPC:	.8
EBI@21C:	1.12 E-11L/cm^2		
TEMP(C):	21 deg C		
Kf =	1.24	EFL in:	27 mm
Nf =	1.54	EFL out:	27 mm
Tcoeff =	3 deg C	CONTRAST:	-1
SENS =	296 uA/L	(T-B)/(T+B)	
Satur:	8.7 FL	SysGain =	1272.
At LL =	1e-2 FL,	Resol =	.764 cy/mr
=	1e-3 FL,	=	.631 cy/mr
=	1e-4 FL,	=	.460 cy/mr
=	1e-5 FL,	=	.293 cy/mr

AN/AVS-6 Monocular Assembly

Image Tube Serial no. 3400 (std. setting)

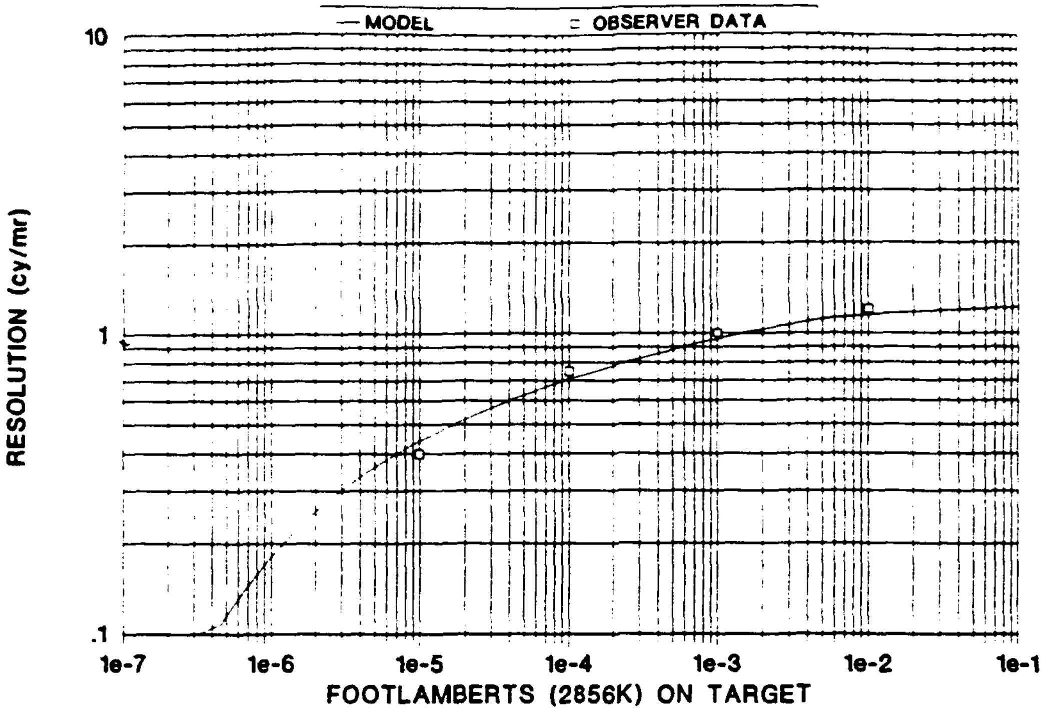


TUBE PARAMETERS:		OPTICS PARAMETERS:	
n:	1.4	fc, n:	70 1.41
Lim Res:	64 Lp/mm	distor =	4.9 %
GEN:	3	T-no:	1.37
FORMAT:	18 mm	FOV:	40 deg
S/N(HL):	17.8	MAG =	1
GAIN:	35100 FL/FC	T-EYEPC:	.8
EBI@21C:	2.26 E-11L/cm^2		
TEMP(C):	21 deg C		
Kf =	1.19	EFL in:	27 mm
Nf =	1.9	EFL out:	27 mm
Tcoeff =	4 deg C	CONTRAST:	-1
SENS =	1078 uA/L		(T-B)/(T+B)
Satur:	100 FL	SysGain =	3740.

At LL =	1e-2 FL,	Resol =	1.139 cy/mr
=	1e-3 FL,	=	.908 cy/mr
=	1e-4 FL,	=	.661 cy/mr
=	1e-5 FL,	=	.413 cy/mr

AN/AVS-6 Monocular Assembly

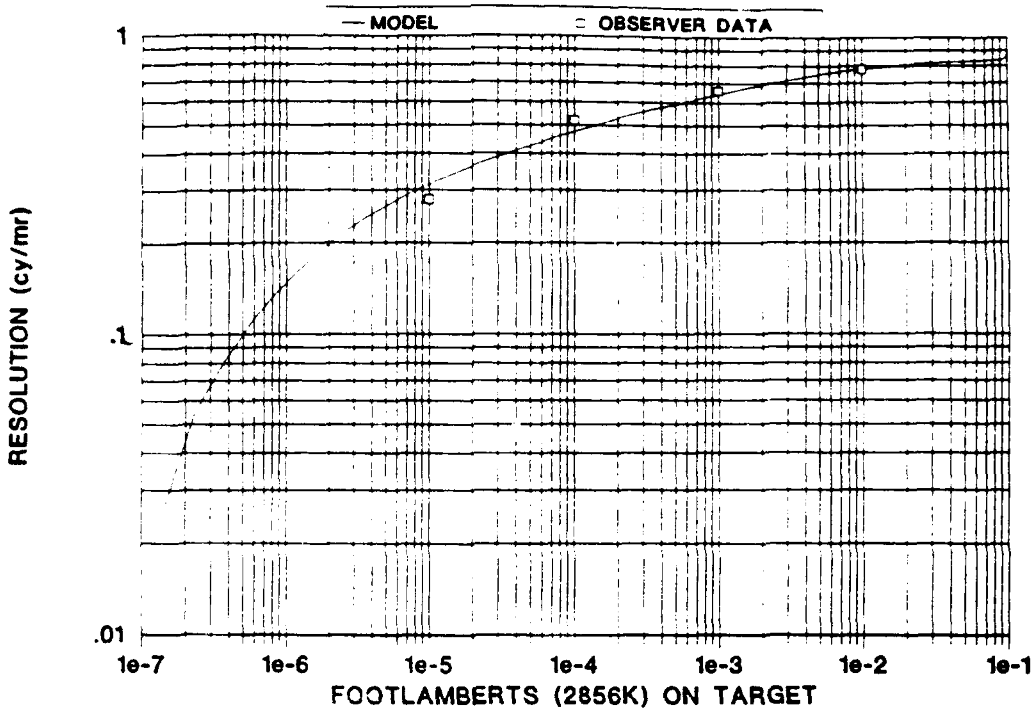
Image Tube Serial no. 3400 (hi gain setting)



TUBE PARAMETERS:			OPTICS PARAMETERS:	
n:	1.4		fc, n:	70 1.41
Lim Res:	64 Lp/mm		distor =	4.9 %
GEN:	3		T-no:	1.37
FORMAT:	18 mm		FOV:	40 deg
S/N(HL):	17.8		MAG =	1
GAIN:	67210 FL/FC		T-EYEPC:	.8
EBI@21C:	2.26 E-11L/cm^2			
TEMP(C):	21 deg C			
Kf =	1.19		EFL in:	27 mm
Nf =	1.9		EFL out:	27 mm
Tcoeff =	4 deg C		CONTRAST:	-1
SENS =	1078 uA/L		(T-B)/(T+B)	
Satur:	44 FL		SysGain =	7162.
At LL =	1e-2 FL,	Resol =	1.146 cy/mr	
=	1e-3 FL,	=	.956 cy/mr	
=	1e-4 FL,	=	.706 cy/mr	
=	1e-5 FL,	=	.441 cy/mr	

AN/AVS-6 Monocular Assembly

Image Tube Serial no. 0708

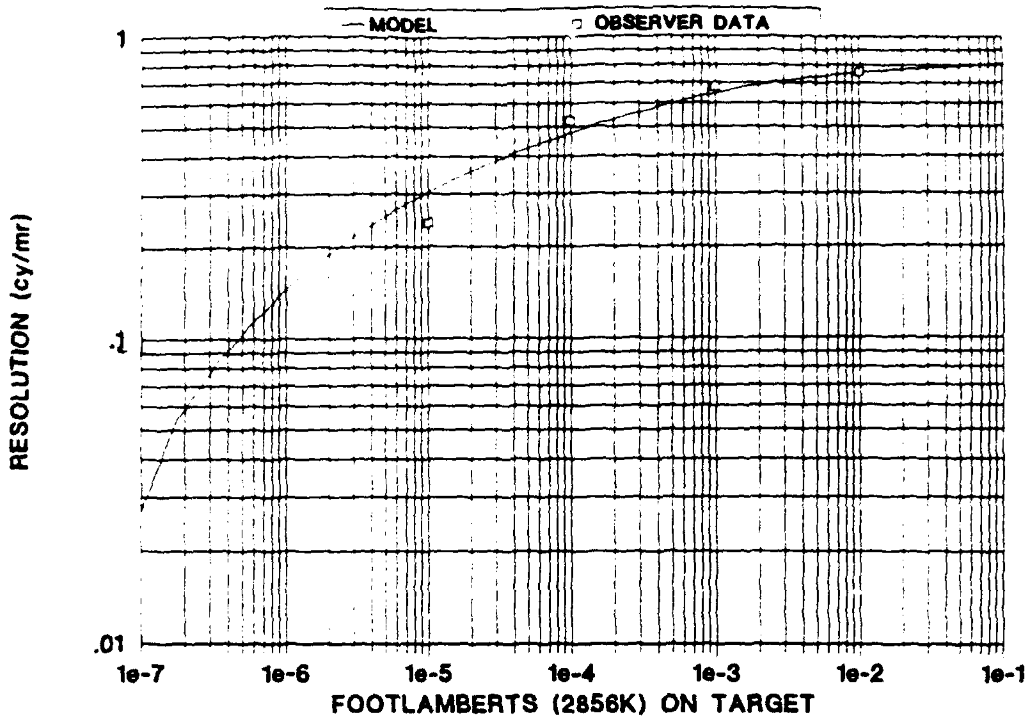


TUBE PARAMETERS:		OPTICS PARAMETERS:	
n:	1.35	fc, n:	70 1.41
Lim Res:	36 Lp/mm	distor =	4.9 %
GEN:	3	T-no:	1.37
FORMAT:	18 mm	FOV:	40 deg
S/N(HL):	18.06	MAG =	1
GAIN:	15300 FL/FC	T-EYEPC:	.8
EBI@21C:	2.32 E-11L/cm^2		
TEMP(C):	21 deg C		
Kf =	1.19	EFL in:	27 mm
Nf =	1.9	EFL out:	27 mm
Tcoeff =	4 deg C	CONTRAST:	-1
SENS =	1110 uA/L	(T-B)/(T+B)	
Satur:	17 FL	SysGain =	1630.

At LL =	1e-2 FL,	Resol	=	.781 cy/mr
=	1e-3 FL,		=	.641 cy/mr
=	1e-4 FL,		=	.476 cy/mr
=	1e-5 FL,		=	.314 cy/mr

AN/PVS-5A Ser. No. 1889A

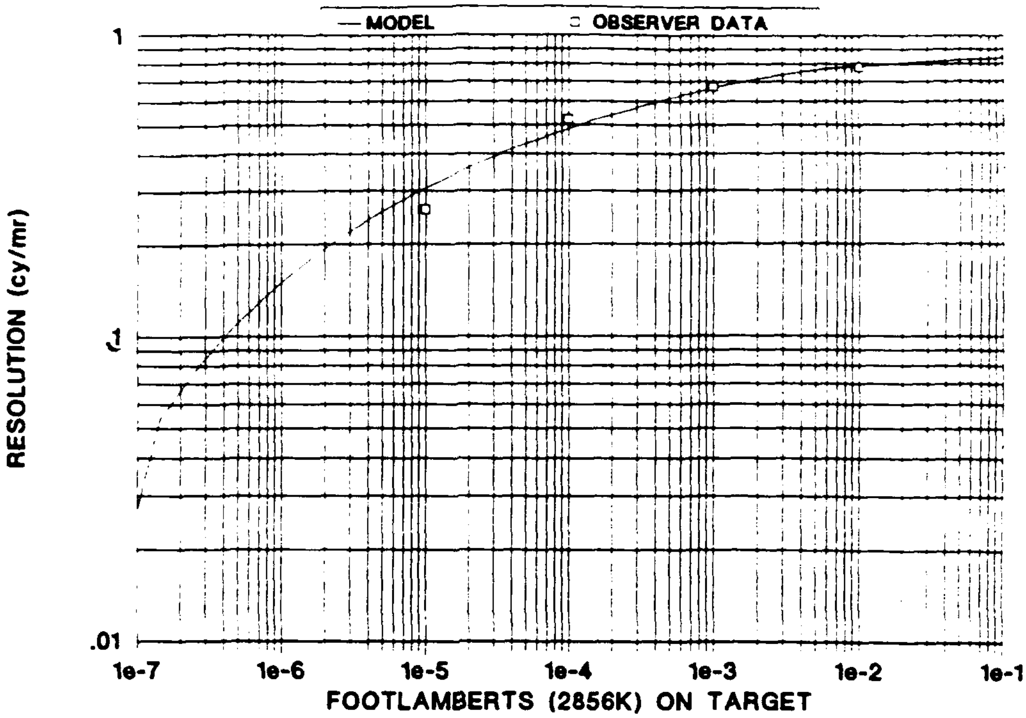
Image Tube Serial nos. 9599 & 268601



TUBE PARAMETERS:			OPTICS PARAMETERS:	
n:	1.25		fc, n:	45 1
Lim Res:	25/32	Lp/mm	distor =	4.9 %
GEN:	2		T-no:	1.62
FORMAT:	18	mm	FOV:	40 deg
S/N(HL):	10.44/12.13		MAG =	1
GAIN:	33500/23750	FL/FC	T-EYEPC:	.8
EBI@21C:	.90/1.31	E-11L/cm^2		
TEMP(C):	21	deg C		
Kf =	1.24		EFL in:	27 mm
Nf =	1.54		EFL out:	27 mm
Tcoeff =	3	deg C	CONTRAST:	-1
SENS =	285	uA/L	(T-B)/(T+B)	
Satur:	15.5/10.8	FL	SysGain =	2181.

At LL =	1e-2 FL,	Resol =	.756 cy/mr
=	1e-3 FL,	=	.643 cy/mr
=	1e-4 FL,	=	.477 cy/mr
=	1e-5 FL,	=	.304 cy/mr

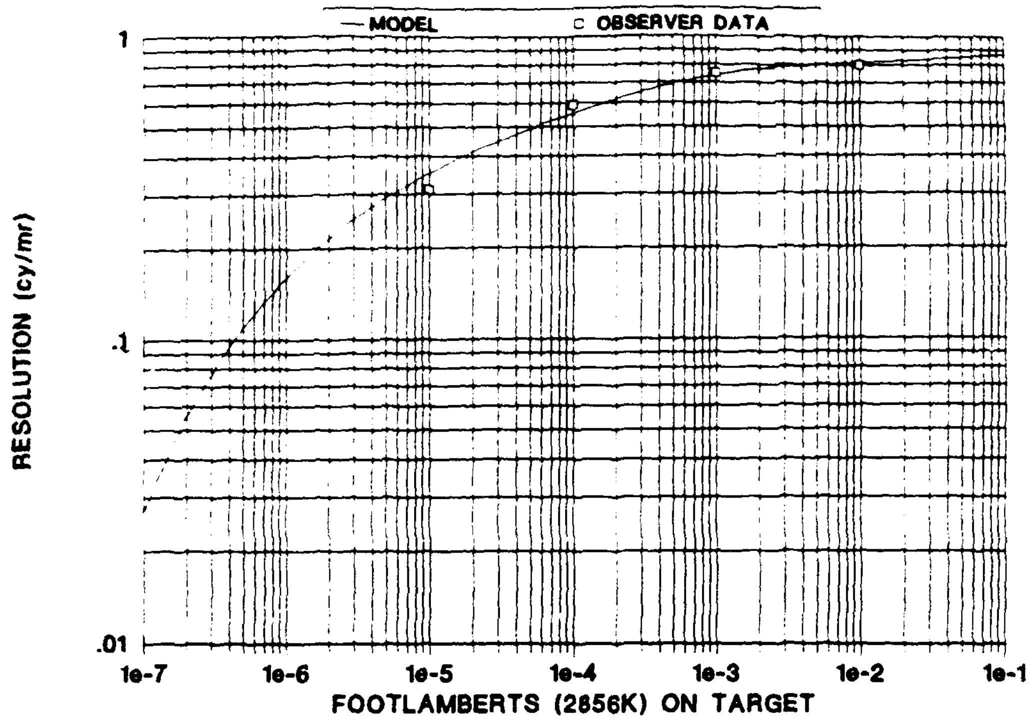
AN/PVS-5A Ser. No. 2250D
Image Tube Serial nos. 267740 & 267592



TUBE PARAMETERS:		OPTICS PARAMETERS:	
n:	1.25	fc, n:	45 1
Lim Res:	32/32 Lp/mm	distor =	4.9 %
GEN:	2	T-no:	1.62
FORMAT:	18 mm	FOV:	40 deg
S/N(HL):	12.13/11.44	MAG =	1
GAIN:	15000/16500 FL/FC	T-EYEPC:	.8
EBI@21C:	.67/.70 E-11L/cm^2		
TEMP(C):	21 deg C		
Kf =	1.24	EFL in:	27 mm
Nf =	1.54	EFL out:	27 mm
Tcoeff =	3 deg C	CONTRAST:	-1
SENS =	310 uA/L		(T-B)/(T+B)
Satur:	8.9/9.5 FL	SysGain =	1200.
At LL =	1e-2 FL,	Resol =	.788 cy/mr
=	1e-3 FL,	=	.663 cy/mr
=	1e-4 FL,	=	.485 cy/mr
=	1e-5 FL,	=	.307 cy/mr

AN/PVS-5C Ser. No. 2706A

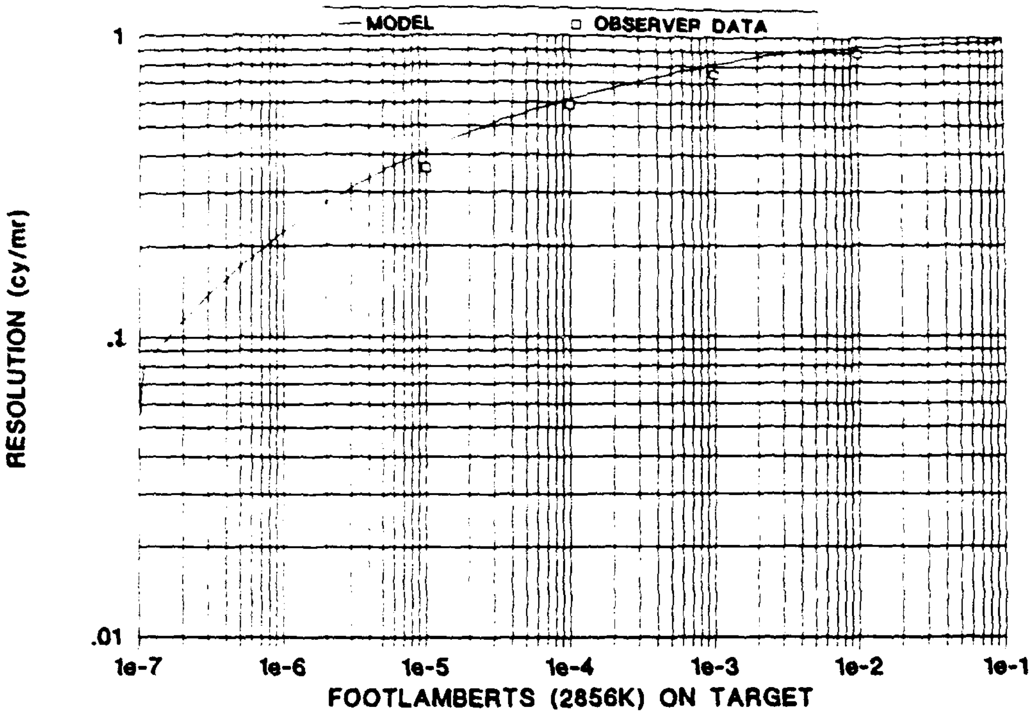
Image Tube Serial nos. 273311 & 277308



TUBE PARAMETERS:			OPTICS PARAMETERS:	
n:	1.25		fc, n:	75 1.7
Lim Res:	32/32 Lp/mm		distor =	4.9 %
GEN:	2		T-no:	1.3
FORMAT:	18 mm		FOV:	40 deg
S/N(HL):	11.15/10.28		MAG =	1
GAIN:	11250/11600 FL/FC		T-EYEPC:	.8
EBI@21C:	3.25/3.34 E-11L/cm^2			
TEMP(C):	21 deg C			
Kf =	1.24		EFL in:	27 mm
Nf =	1.54		EFL out:	27 mm
Tcoeff =	3 deg C		CONTRAST:	-1
SENS =	257 uA/L		(T-B)/(T+B)	
Satur:	3.3/3.5 FL		SysGain =	1352.
At LL =	1e-2 FL,	Resol	=	.817 cy/mr
=	1e-3 FL,		=	.740 cy/mr
=	1e-4 FL,		=	.553 cy/mr
=	1e-5 FL,		=	.351 cy/mr

ANVIS, AN/AVS-6 Ser. No. 5065A

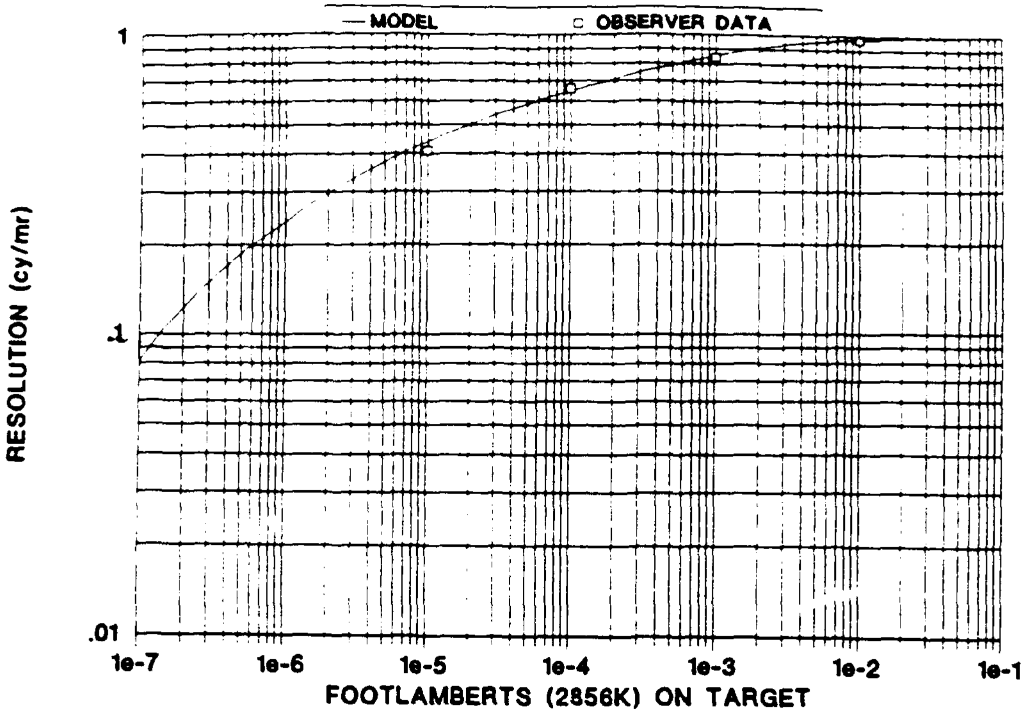
Image Tube Serial nos. 145179 & 105248



TUBE PARAMETERS:		OPTICS PARAMETERS:	
n:	1.3	fc, n:	70 1.41
Lim Res:	36/32 Lp/mm	distor =	4.9 %
GEN:	3	T-no:	1.37
FORMAT:	18 mm	FOV:	40 deg
S/N(HL):	16.38/15.80	MAG =	1
GAIN:	21650/23250 FL/FC	T-EYEPC:	.8
EBI@21C:	.18/.72 E-11L/cm^2		
TEMP(C):	21 deg C		
Kf =	1.19	EFL in:	27 mm
Nf =	1.9	EFL out:	27 mm
Tcoeff =	4 deg C	CONTRAST:	-1
SENS =	881 uA/L		(T-B)/(T+B)
Satur:	13.2/14.2 FL	SysGain =	2392.

At LL =	1e-2 FL,	Resol =	.929 cy/mr
=	1e-3 FL,	=	.813 cy/mr
=	1e-4 FL,	=	.616 cy/mr
=	1e-5 FL,	=	.413 cy/mr

ANVIS, AN/AVS-6 Ser. No. 8825A
Image Tube Serial nos. 131755 & 131838

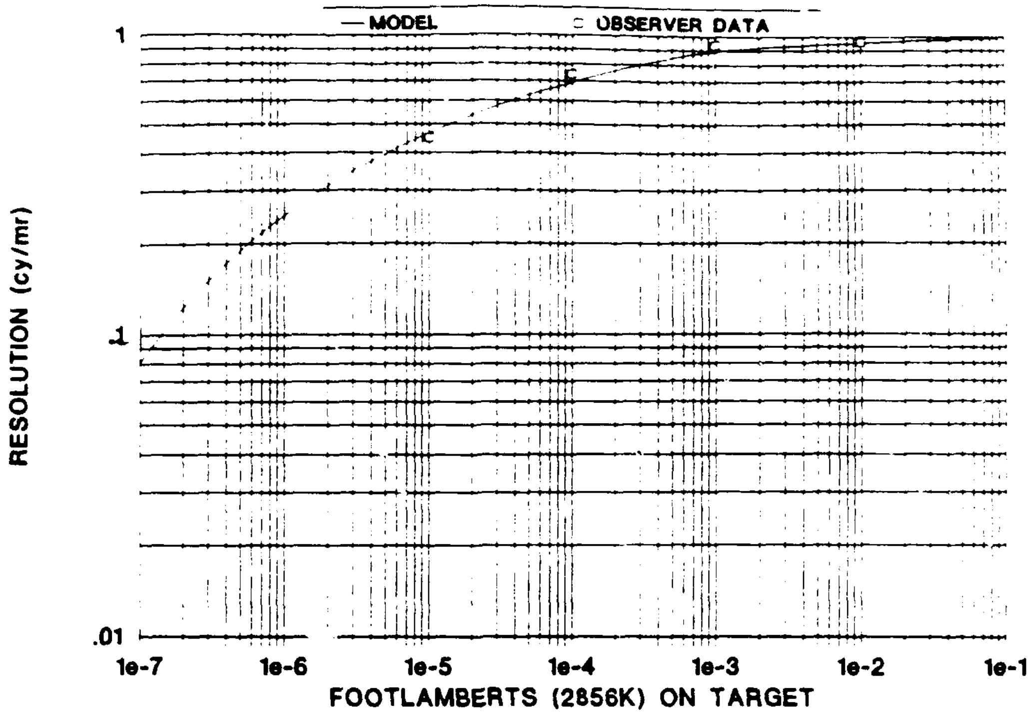


TUBE PARAMETERS:		OPTICS PARAMETERS:	
n:	1.3	fc, n:	70 1.41
Lim Res:	36/36 Lp/mm	distor =	4.9 %
GEN:	3	T-no:	1.37
FORMAT:	18 mm	FOV:	40 deg
S/N(HL):	17.90/18.12	MAG =	1
GAIN:	25900/27600 FL/FC	T-EYEPC:	.8
EBI@21C:	.47/.45 E-11L/cm^2		
TEMP(C):	21 deg C		
Kf =	1.19	EFL in:	27 mm
Nf =	1.9	EFL out:	27 mm
Tcoeff =	4 deg C	CONTRAST:	-1
SENS =	1104 uA/L		(T-B)/(T+B)
Satur:	19/19 FL	SysGain =	2850.

At LL =	1e-2 FL,	Resol =	.979 cy/mr
=	1e-3 FL,	=	.851 cy/mr
=	1e-4 FL,	=	.648 cy/mr
=	1e-5 FL,	=	.438 cy/mr

ANVIS, AN/AVS-6 Ser. No. 17566B

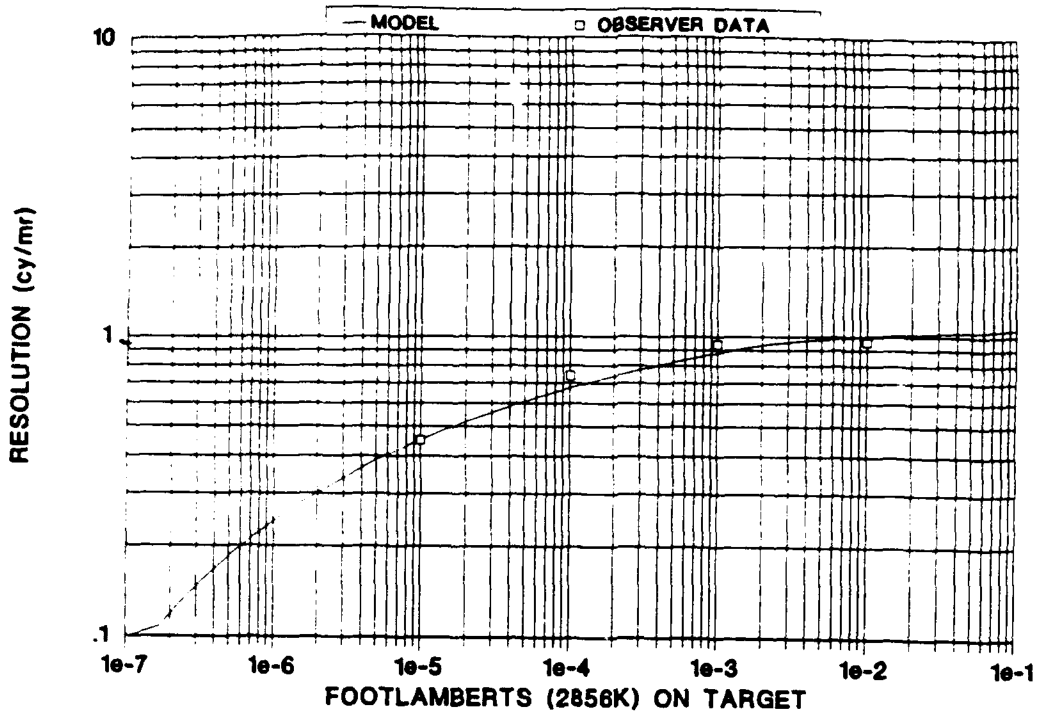
Image Tube Serial nos. 45221 & 46014



TUBE PARAMETERS:		OPTICS PARAMETERS:	
n:	1.45	fc, n:	70 1.41
Lim Res:	40/40 Lp/mm	distor =	4.9 %
GEN:	3	T-no:	1.37
FORMAT:	18 mm	FOV:	40 deg
S/N(HL):	17.68/17.38	MAG =	1
GAIN:	26000/24250 FL/FC	T-EYEPC:	.8
EBI@21C:	.56/.41 E-11L/cm^2		
TEMP(C):	21 deg C		
Kf =	1.19	EFL in:	27 mm
Nf =	1.9	EFL out:	27 mm
Tcoeff =	4 deg C	CONTRAST:	-1
SENS =	1046 uA/L	(T-B)/(T+B)	
Satur:	5/5 FL	SysCain =	2677.

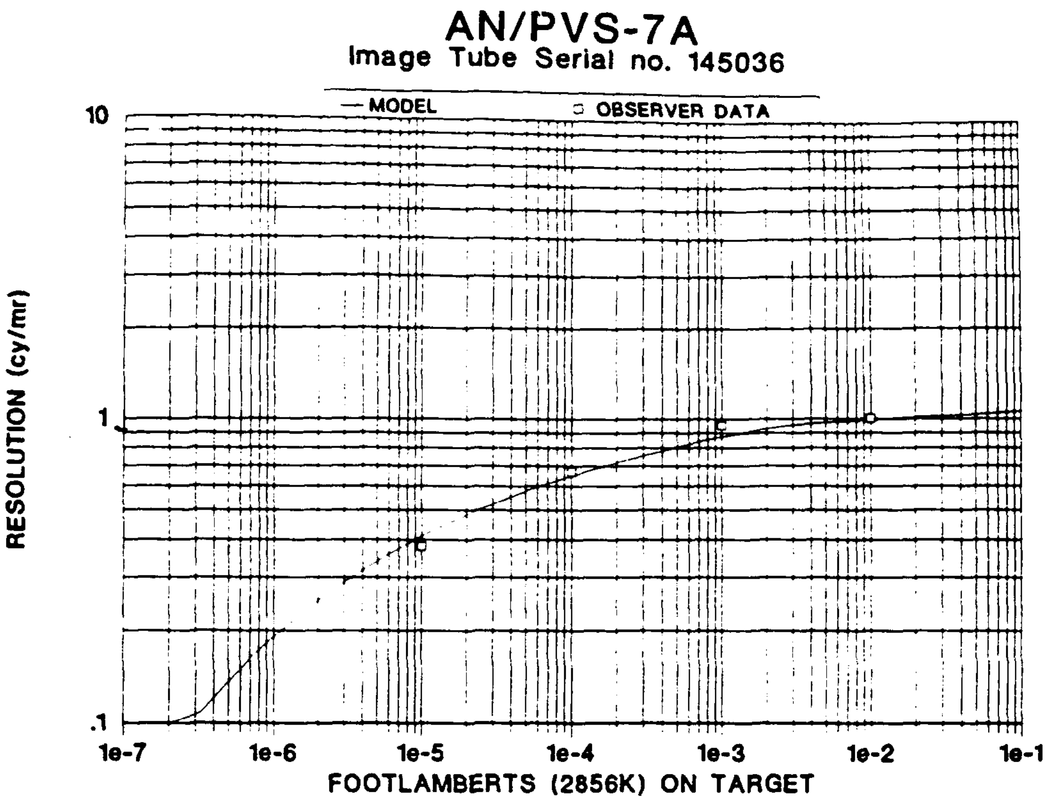
At LL =	1e-2 FL,	Resol =	.957 cy/mr
=	1e-3 FL,	=	.891 cy/mr
=	1e-4 FL,	=	.694 cy/mr
=	1e-5 FL,	=	.466 cy/mr

ANVIS, AN/AVS-6 Ser. No. 17567B
Image Tube Serial nos. 45094 & 42459



TUBE PARAMETERS:		OPTICS PARAMETERS:	
n:	1.45	fc, n:	70 1.41
Lim Res:	40/36 Lp/mm	distor =	4.9 %
GEN:	3	T-no:	1.37
FORMAT:	18 mm	FOV:	40 deg
S/N(HL):	17.25/18.25	MAG =	1
GAIN:	28800/17100 FL/FC	T-EYEPC:	.8
EBI@21C:	.82/.45 E-11L/cm^2		
TEMP(C):	21 deg C		
Kf =	1.19	EFL in:	27 mm
Nf =	1.9	EFL out:	27 mm
Tcoeff =	4 deg C	CONTRAST:	-1
SENS =	1072 uA/L		(T-B)/(T+B)
Satur:	13.1/12.1 FL	SysGain =	2446.

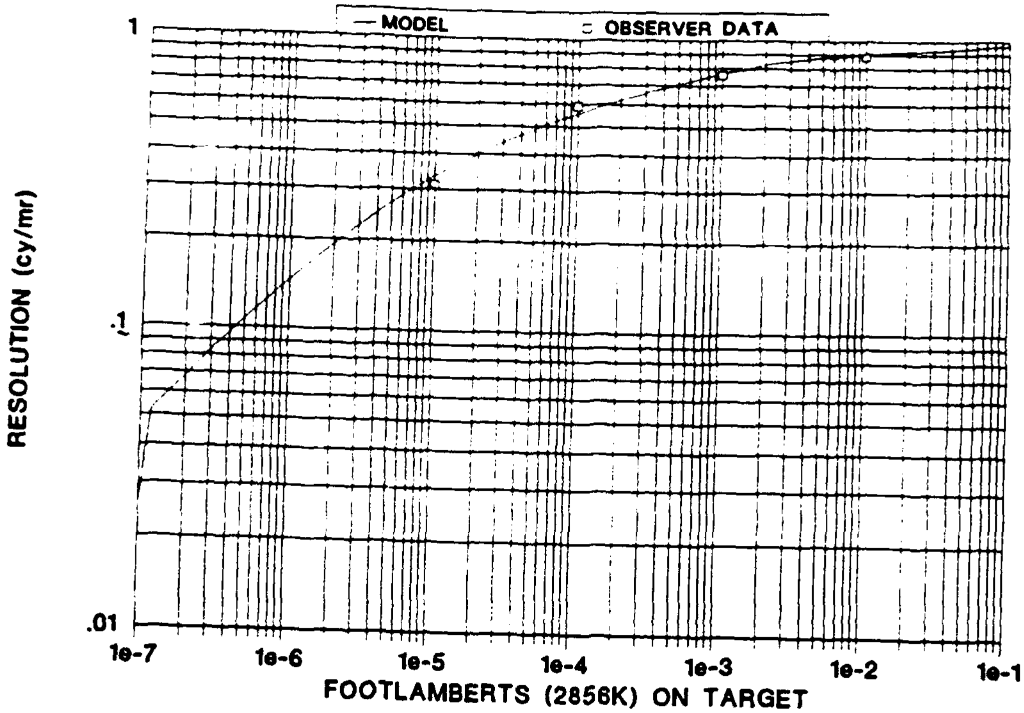
At LL =	1e-2 FL,	Resol =	.998 cy/mr
=	1e-3 FL,	=	.883 cy/mr
=	1e-4 FL,	=	.673 cy/mr
=	1e-5 FL,	=	.453 cy/mr



TUBE PARAMETERS:			OPTICS PARAMETERS:	
n:	1.4		fc, n:	70 1.41
Lim Res:	42/42 Lp/mm		distor =	4.9 %
GEN:	3		T-no:	1.3
FORMAT:	18 mm		FOV:	40 deg
S/N(HL):	16		MAG =	1
GAIN:	23000/23000 FL/FC		T-EYEPC:	.7
EBI@21C:	1.22/1.22 E-11L/cm^2			
TEMP(C):	21 deg C			
Kf =	1.19		EFL in:	27 mm
Nf =	1.9		EFL out:	27 mm
Tcoeff =	4 deg C		CONTRAST:	-1
SENS =	871 uA/L		(T-B)/(T+B)	
Satur:	13/13 FL		SysGain =	2382.
At LL =	1e-2 FL,	Resol =		.992 cy/mr
=	1e-3 FL,	=		.870 cy/mr
=	1e-4 FL,	=		.646 cy/mr
=	1e-5 FL,	=		.410 cy/mr

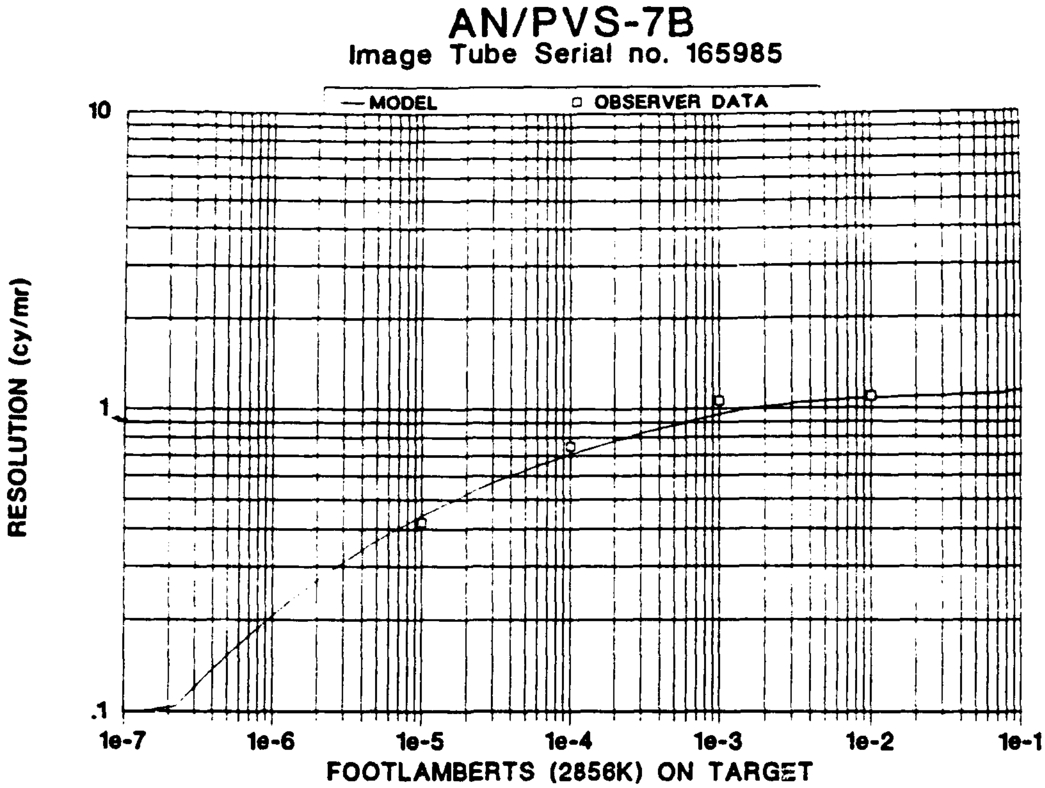
AN/PVS-7B

Image Tube Serial no. 108183



TUBE PARAMETERS:		OPTICS PARAMETERS:	
n:	1.4	fc, n:	70 1.41
Lim Res:	38/38 Lp/mm	distor =	.9 %
GEN:	3	T-no:	1.3
FORMAT:	18 mm	FOV:	40 deg
S/N(HL):	11.6	MAG =	1
GAIN:	17750/17750 FL/FC	T-EYEPC:	.7
EBI@21C:	.15/.15 E-11L/cm^2		
TEMP(C):	21 deg C		
Kf =	1.19	EFL in:	26 mm
Nf =	1.9	EFL out:	26 mm
Tcoeff =	4 deg C	CONTRAST:	-1
SENS =	458 uA/L		(T-B)/(T+B)
Satur:	11.8/11.8 FL	SysGain =	1838.

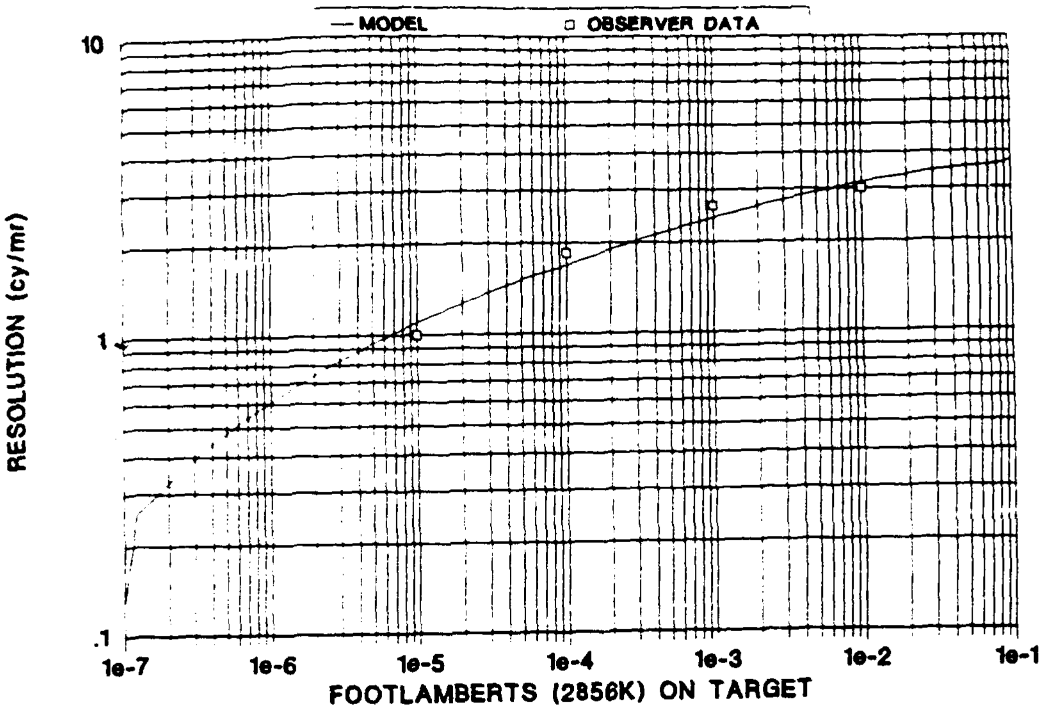
At LL =	1e-2 FL,	Resol =	.901 cy/mr
=	1e-3 FL,	=	.768 cy/mr
=	1e-4 FL,	=	.556 cy/mr
=	1e-5 FL,	=	.333 cy/mr



TUBE PARAMETERS:		OPTICS PARAMETERS:	
n:	1.45	fc, n:	70 1.41
Lim Res:	53.5/53.5 Lp/mm	distor =	.9 %
GEN:	3	T-no:	1.3
FORMAT:	18 mm	FOV:	40 deg
S/N(HL):	17.8	MAG =	1
GAIN:	25000/25000 FL/FC	T-EYEPC:	.7
EBI@21C:	.3/.3 E-11L/cm^2		
TEMP(C):	21 deg C		
Kf =	1.19	EFL in:	26 mm
Nf =	1.9	EFL out:	26 mm
Tcoeff =	4 deg C	CONTRAST:	-1
SENS =	1078 uA/L		(T-B)/(T+B)
Satur:	13.1/13.1 FL	SysGain =	2589.

At LL =	1e-2 FL,	Resol	=	1.078 cy/mr
=	1e-3 FL,		=	.953 cy/mr
=	1e-4 FL,		=	.704 cy/mr
=	1e-5 FL,		=	.442 cy/mr

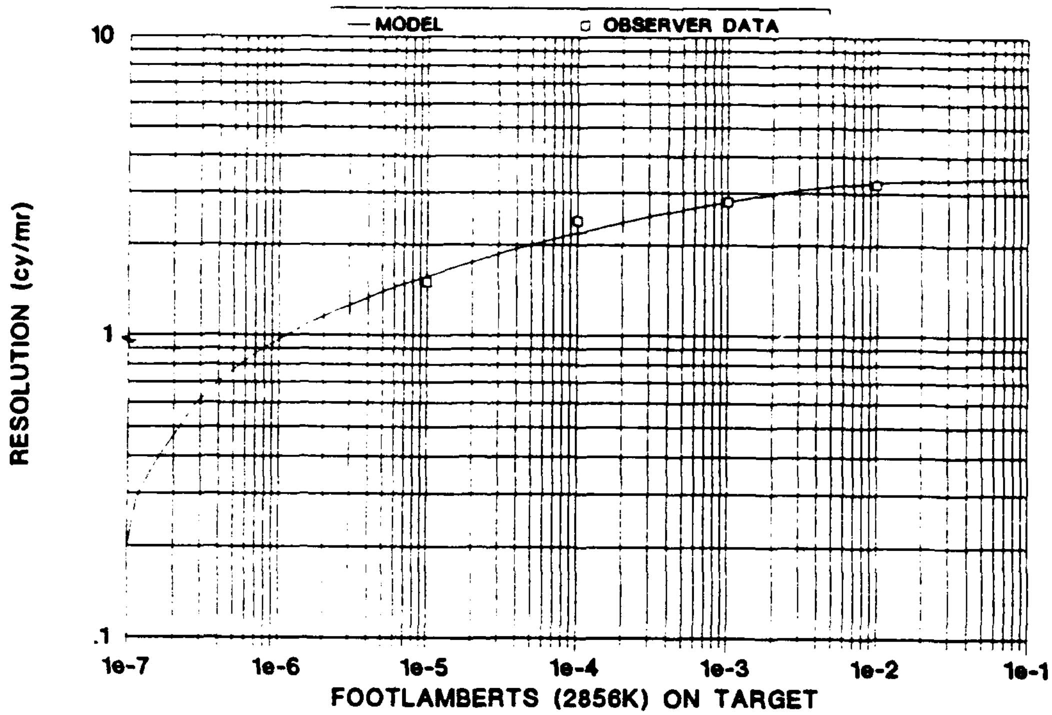
3.6X Weapon Sight
Image Tube Serial no. 1014



TUBE PARAMETERS:			OPTICS PARAMETERS:	
n:	1.25		fc, n:	45 1.2
Lim Res:	40 Lp/mm		distor =	-.2 %
GEN:	3		T-no:	2.2
FORMAT:	18 mm		FOV:	8 deg
S/N(HL):	16.56		MAG =	3.6
GAIN:	17500 FL/FC		T-EYEPC:	.7
EBI@21C:	.16 E-11L/cm^2			
TEMP(C):	21 deg C			
Kf =	1.19		EFL in:	128.7 mm
Nf =	1.9		EFL out:	35.75 mm
Tcoeff =	4 deg C		CONTRAST:	-1
SENS =	933 uA/L		(T-B)/(T+B)	
Satur:	25 FL		SysGain =	632.7
At LL =	1e-2 FL,	Resol =	3.147 cy/mr	
=	1e-3 FL,	=	2.407 cy/mr	
=	1e-4 FL,	=	1.688 cy/mr	
=	1e-5 FL,	=	1.101 cy/mr	

4X Weapon Sight

Image Tube Serial no. 4E-475

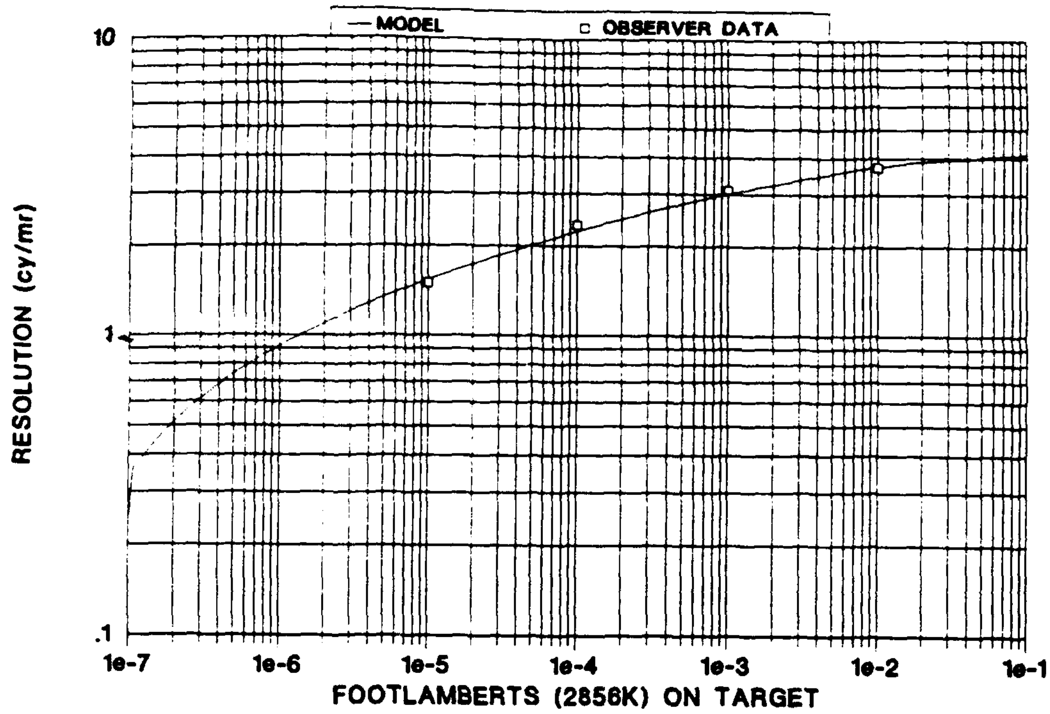


TUBE PARAMETERS:		**OPTICS PARAMETERS:**	
n:	1.25	fc, n:	50 1.2
Lim Res:	40 Lp/mm	distor =	-3.1 %
GEN:	2	T-no:	1.3
FORMAT:	18 mm	FOV:	10 deg
S/N(HL):	15.7	MAG =	4
GAIN:	48650 FL/FC	T-EYEPC:	.8
EBI@21C:	1.38 E-11L/cm^2		
TEMP(C):	21 deg C		
Kf =	1.19	EFL in:	100 mm
Nf =	1.54	EFL out:	25 mm
Tcoef =	3 deg C	CONTRAST:	-1
SENS =	551 uA/L	(T-B)/(T+B)	
Satur:	100 FL	SysGain =	5757.

At LL =	1e-2 FL,	Resol =	3.269 cy/mr
=	1e-3 FL,	=	2.809 cy/mr
=	1e-4 FL,	=	2.193 cy/mr
=	1e-5 FL,	=	1.564 cy/mr

4.3X Weapon Sight

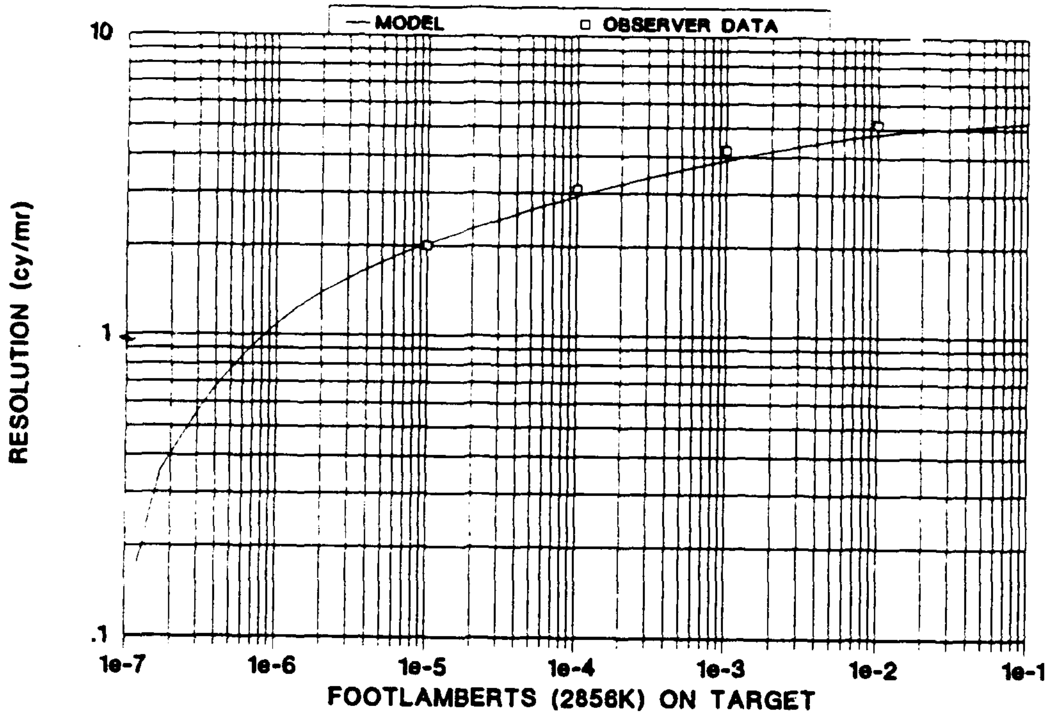
Image Tube Serial no. 007284



TUBE PARAMETERS:			OPTICS PARAMETERS:	
n:	1.25		fc, n:	50 1.2
Lim Res:	42 Lp/mm		distor =	-3.0 %
GEN:	3		T-no:	1.85
FORMAT:	18 mm		FOV:	8.3 deg
S/N(HL):	15.37		MAG =	4.303
GAIN:	35000 FL/FC		T-EYEPC:	.8
EBI@21C:	.26 E-11L/cm^2			
TEMP(C):	21 deg C			
Kf =	1.19		EFL in:	120.7 mm
Nf =	1.9		EFL out:	28.05 mm
Tcoeff =	4 deg C		CONTRAST:	-1
SENS =	804 uA/L		(T-B)/(T+B)	
Satur:	36 FL		SysGain =	2045.
At LL =	1e-2 FL,	Resol =	3.740 cy/mr	
=	1e-3 FL,	=	3.005 cy/mr	
=	1e-4 FL,	=	2.238 cy/mr	
=	1e-5 FL,	=	1.539 cy/mr	

6X Weapon Sight

Image Tube Serial no. 3319



TUBE PARAMETERS:			OPTICS PARAMETERS:		
n:	1.3		fc, n:	49	1
Lim Res:	34 Lp/mm		distor =	-7.8 %	
GEN:	3		T-no:	2	
FORMAT:	18 mm		FOV:	5.5 deg	
S/N(HL):	17.92		MAG =	6.084	
GAIN:	37550 FL/FC		T-EYEPC:	.85	
EBI@21C:	1.8 E-11L/cm^2				
TEMP(C):	21 deg C				
Kf =	1.19		EFL in:	174 mm	
Nf =	1.9		EFL out:	28.6 mm	
Tcoeff =	4 deg C		CONTRAST:	-1	
SENS =	1093 uA/L		(T-B)/(T+B)		
Satur:	36 FL		SysGain =	1995.	
At LL =	1e-2 FL,	Resol =	4.777 cy/mr		
=	1e-3 FL,	=	3.880 cy/mr		
=	1e-4 FL,	=	2.925 cy/mr		
=	1e-5 FL,	=	2.022 cy/mr		

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